Lecture 15

Recap

GEOL 4397: Electromagnetic Methods for Exploration
GEOL 6398: Special Problems

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Nov. 6th, 2018

UNIVERSITY of HOUSTON
YOU ARE THE PRIDE
EARTH AND ATMOSPHERIC SCIENCES

Agenda

- DC resistivity
- RL circuit
- Plane waves
- Inductive source EM
- Grounded source EM

DC Resistivity

- Understanding the secondary charges that are built up on the boundaries of anomalous bodies
- Understanding apparent resistivity (an average measure of the subsurface resistivities)
- Understanding sounding and profiling
- Being able to interpret the sounding and profiling curves
- Understanding the shielding problem in DC resistivity survey

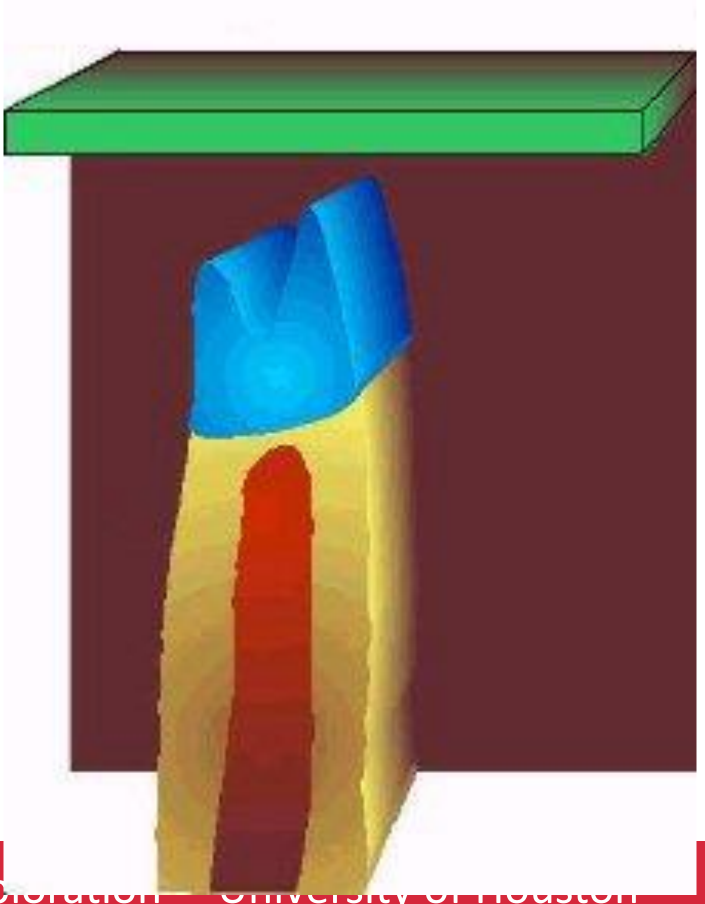
Basic Experiment

- **Target:**

  Ore body. Mineralized regions less resistive than host

Elura Orebody Electrical resistivities

Rock Type	*Ohm-m*
Overburden	12
Host rocks	200
Gossan	420
Mineralization (pyritic)	0.6
Mineralization (pyrrhotite)	0.6



Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

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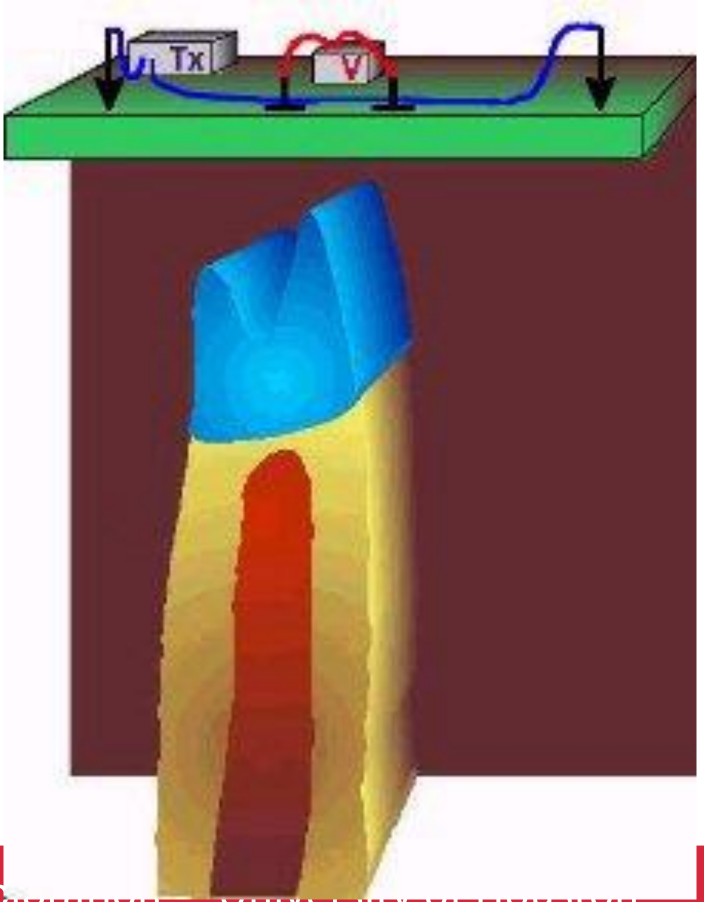
  Tx: Current electrodes

  Rx: Potential electrodes



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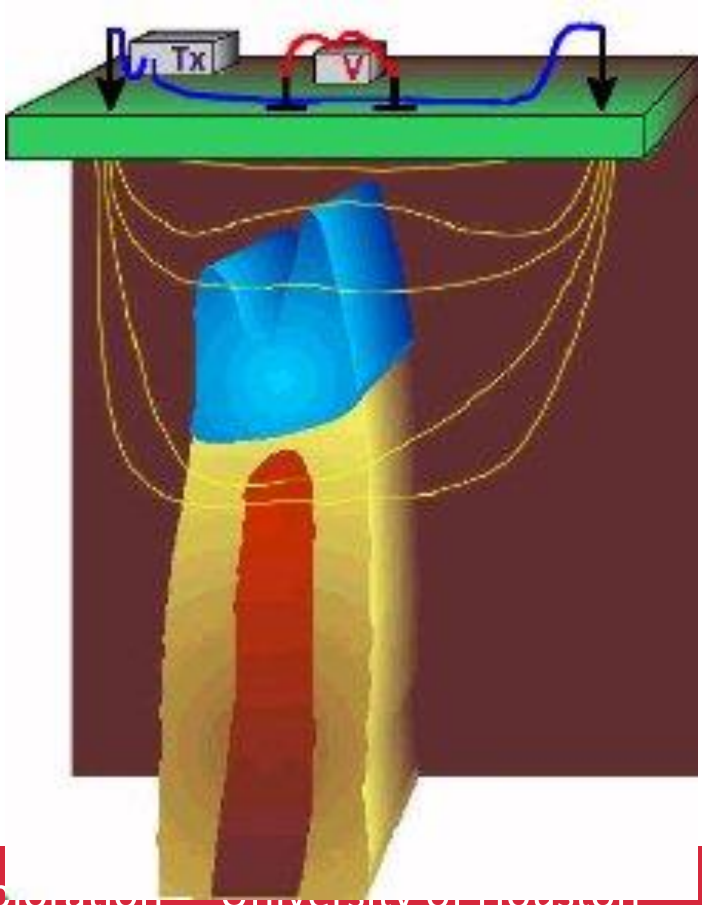

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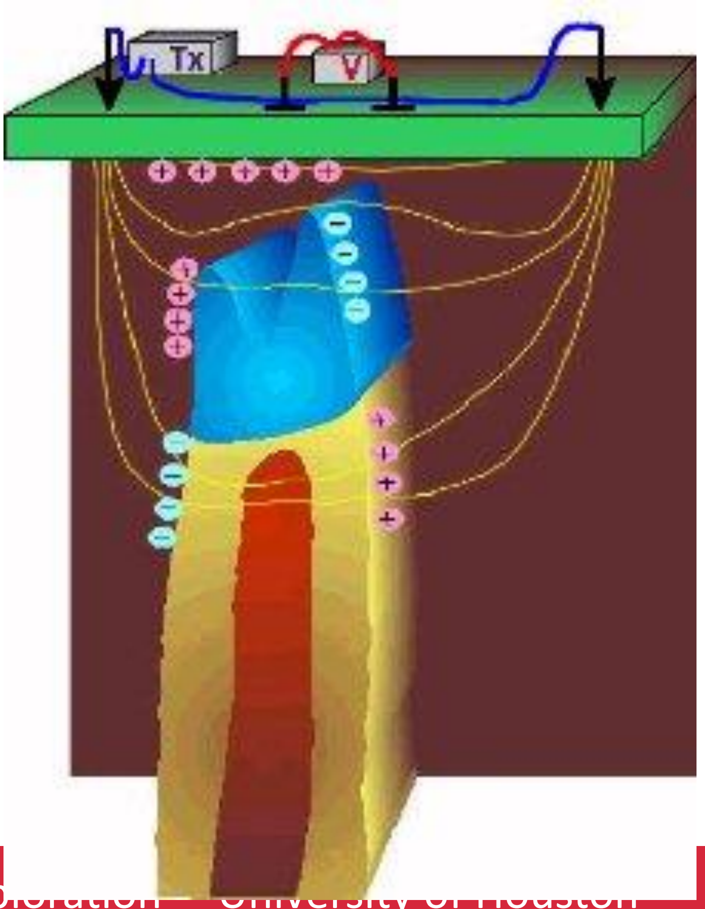

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Basic Experiment

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- **Setup:**

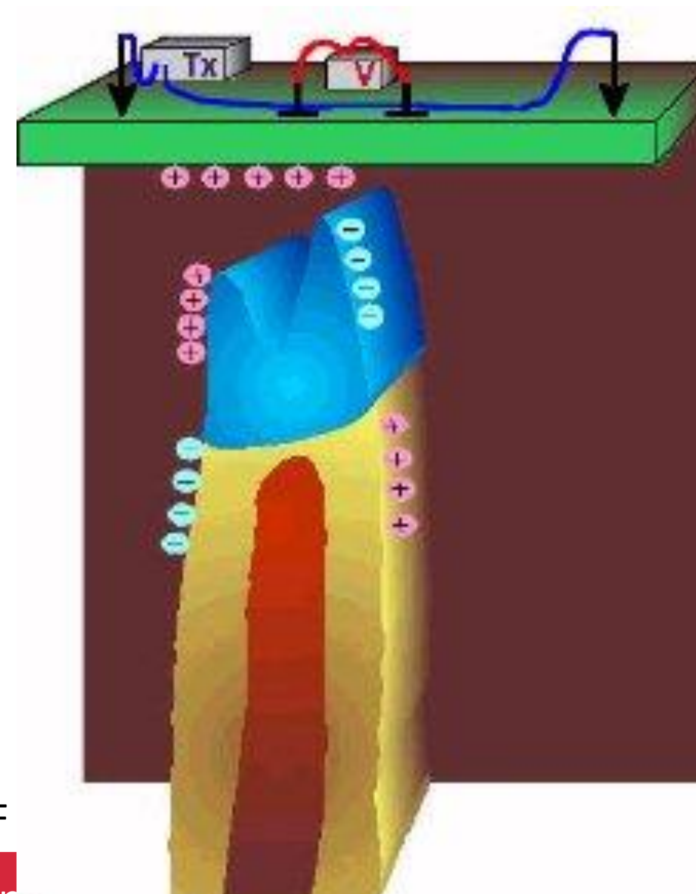
  Tx: Current electrodes

  Rx: Potential electrodes
- **Currents:**

  Preferentially flow through conductors
- **Charges:**

  Build up at interfaces
- **Potentials:**

  Associated with the charges are measured at the surface



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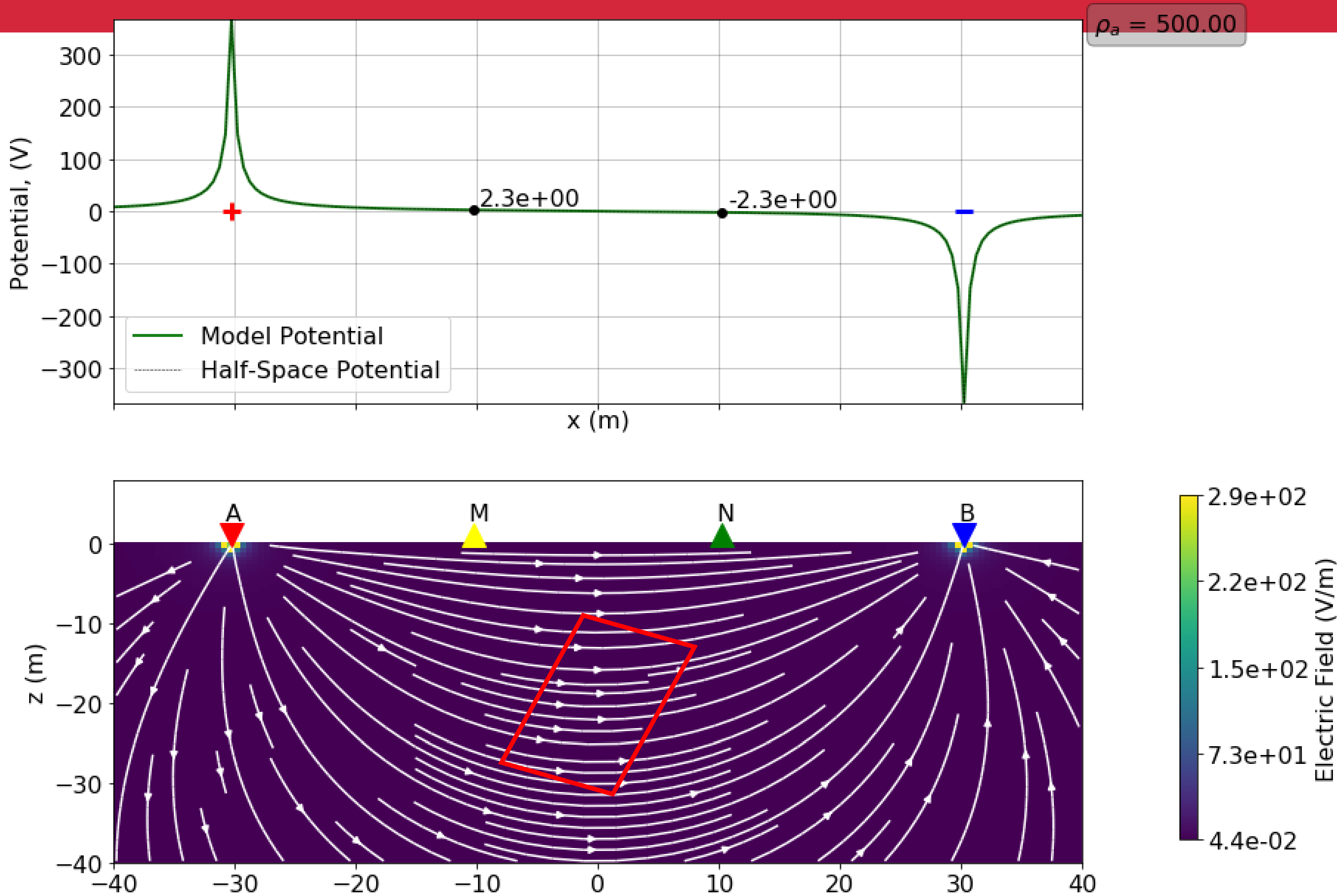
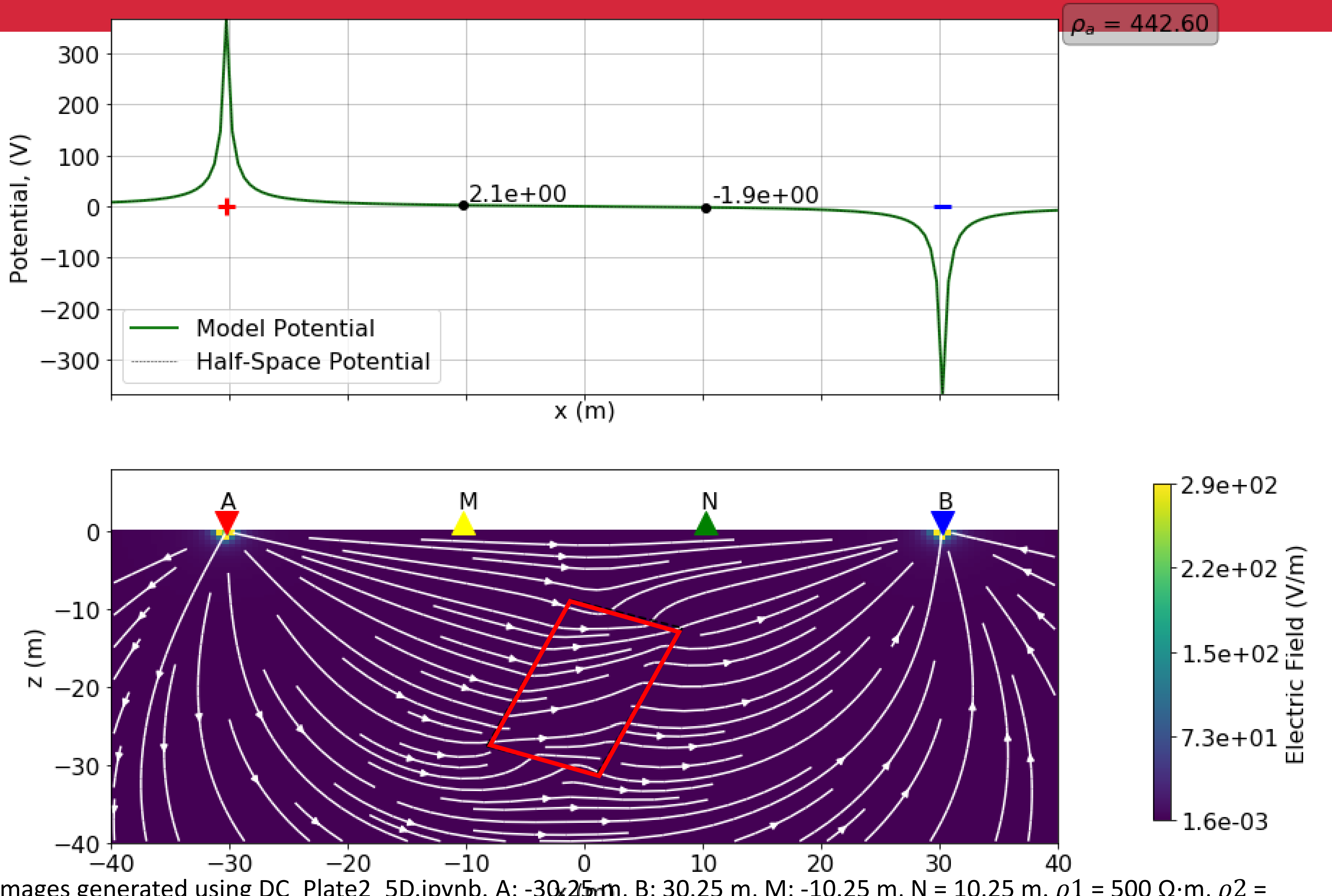


Images generated using DC_Plate2_5D.ipynb. A: -30.25 m, B: 30.25 m, M: -10.25 m, N = 10.25 m. $\rho 1$ = 500 Ω·m, $\rho 2$ = 500 Ω·m. dx = 10, dz=20, xc = 0, zc = -20, theta = 21.



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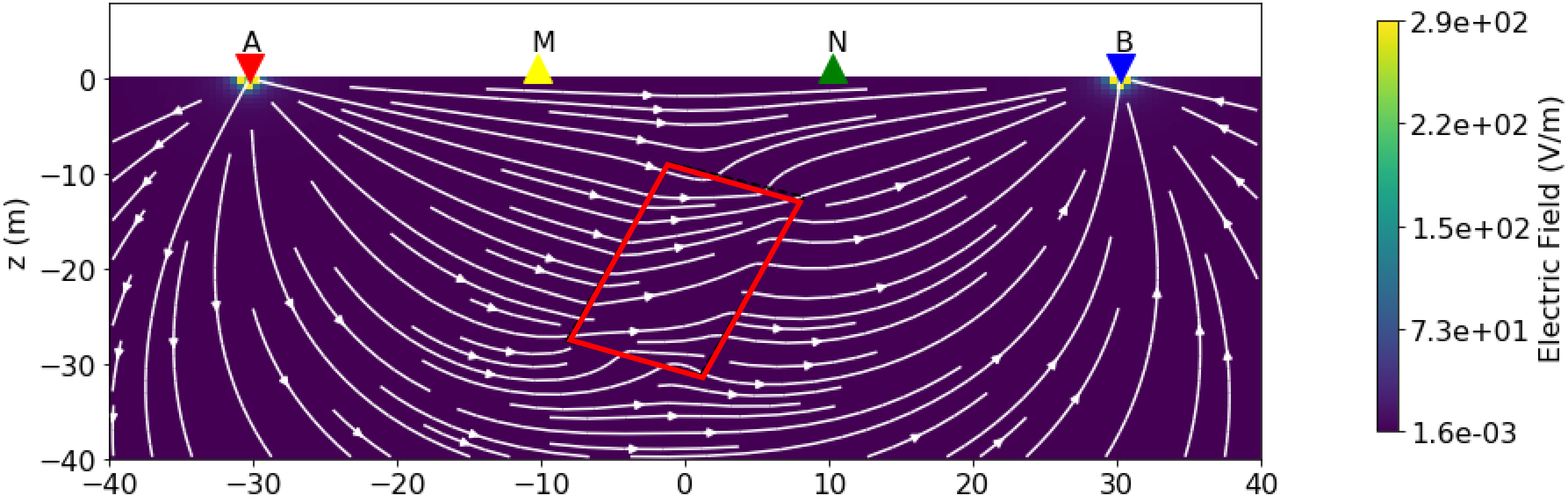
- What could have happened?



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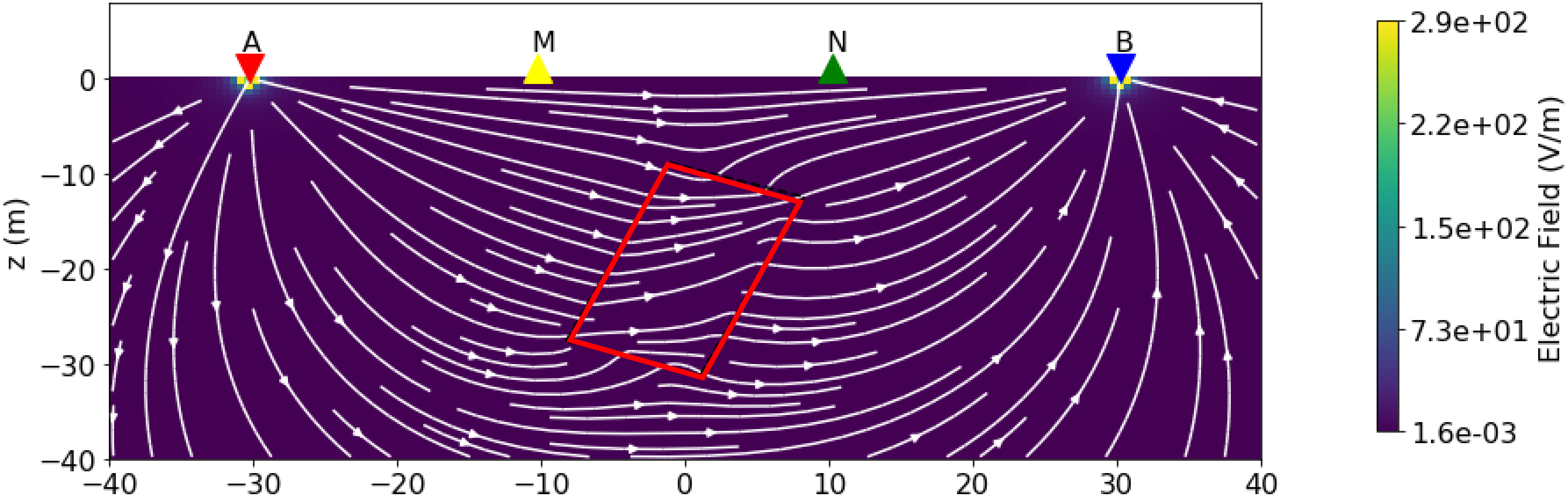
- What could have happened?

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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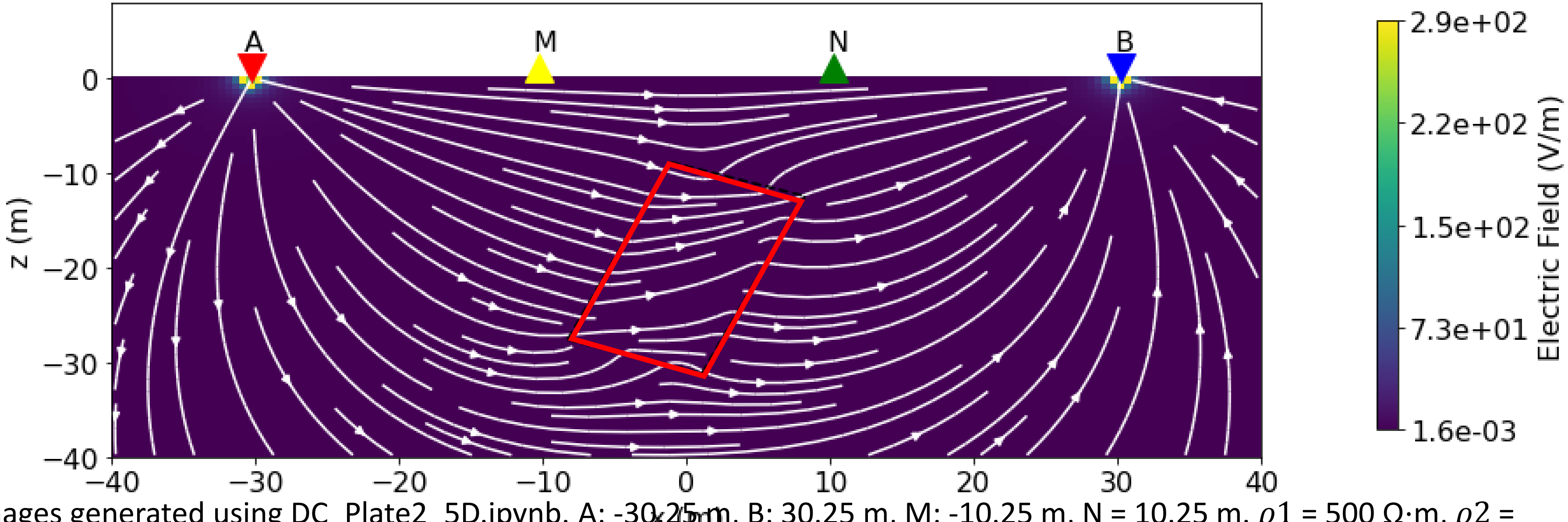
- What could have happened?

- The electric field becomes discontinuous across the boundary.

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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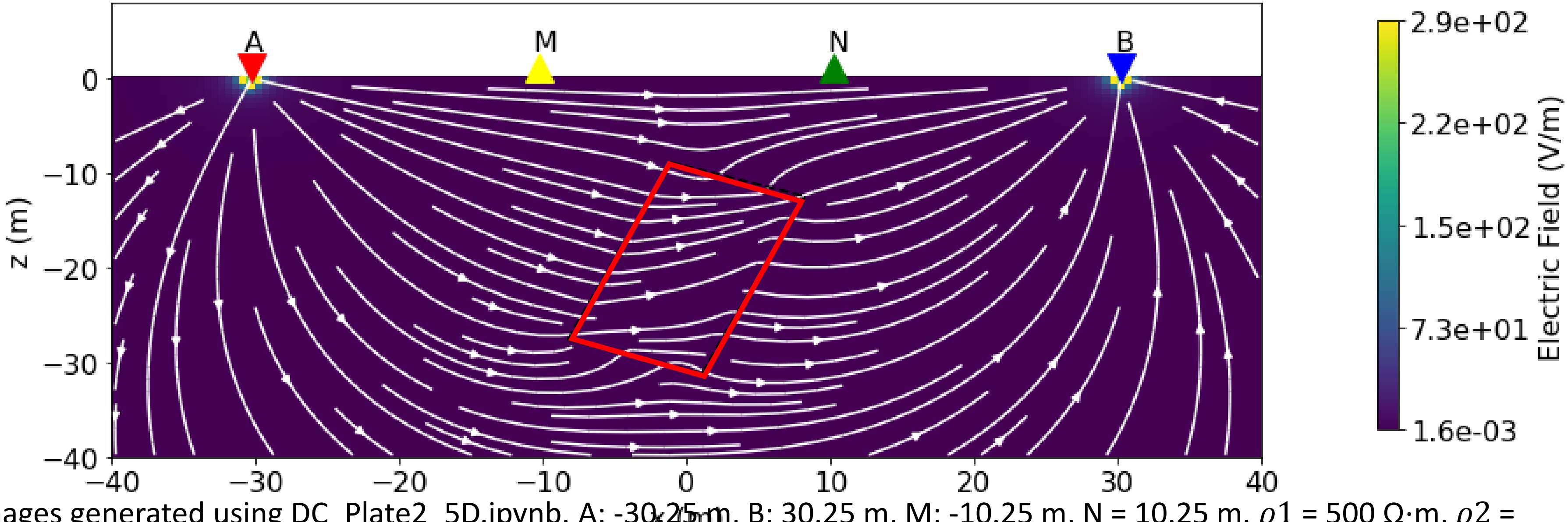
- What could have happened?
- The electric field becomes discontinuous across the boundary.
- What causes the electric field to be discontinuous?

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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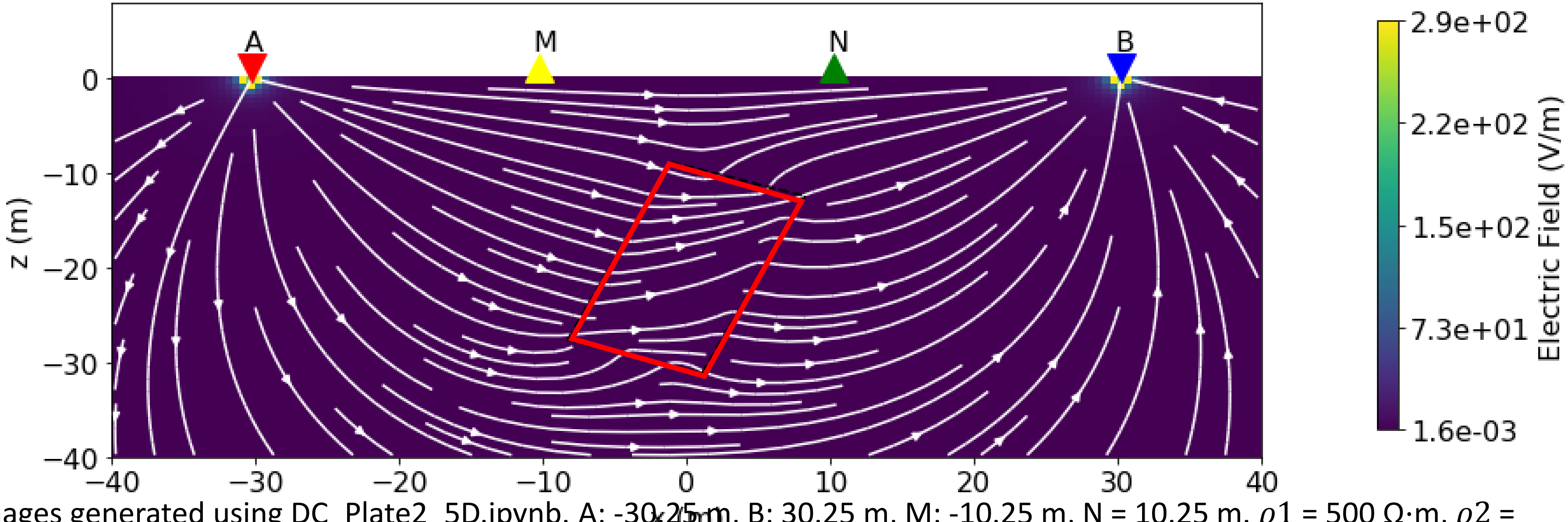
- What could have happened?
- The electric field becomes discontinuous across the boundary.
- What is the easiest way to make the electric field discontinuous?

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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- What could have happened?

- The electric field becomes discontinuous across the boundary.

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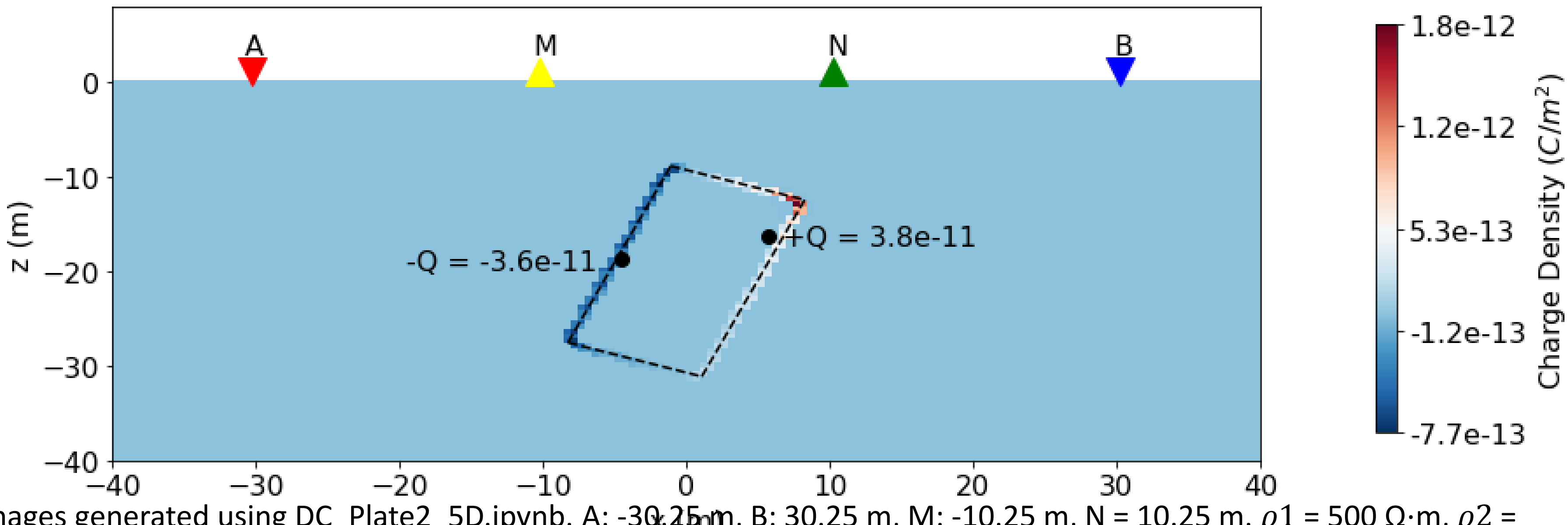
$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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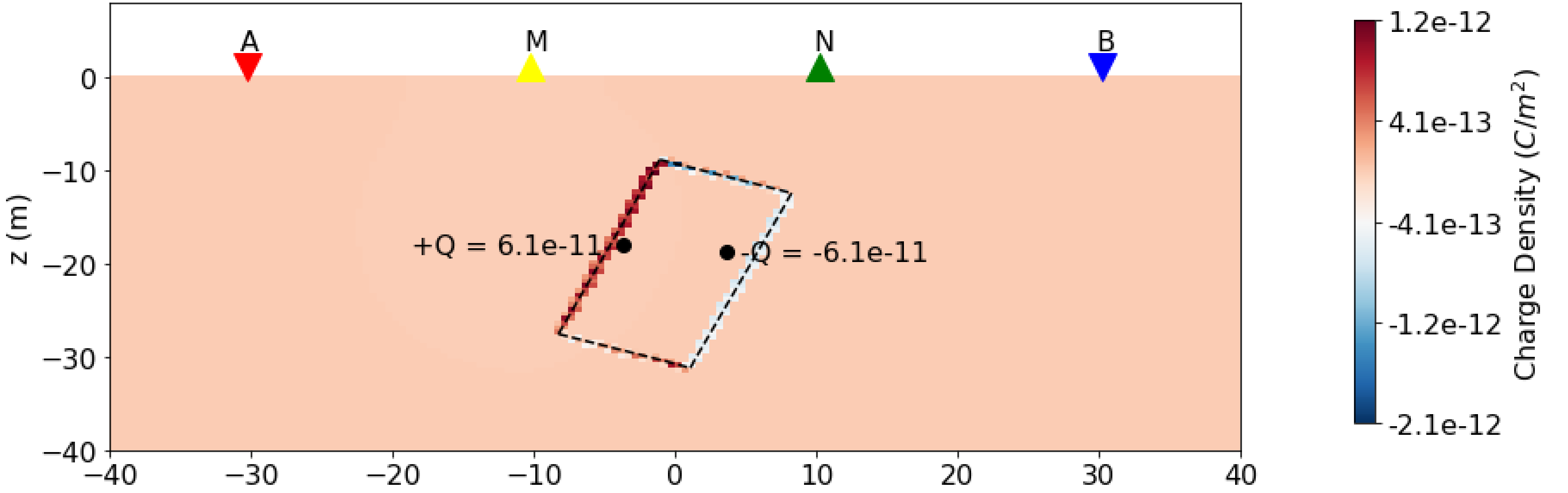
How about a resistor?

- What is the easiest way to make the electric field discontinuous?

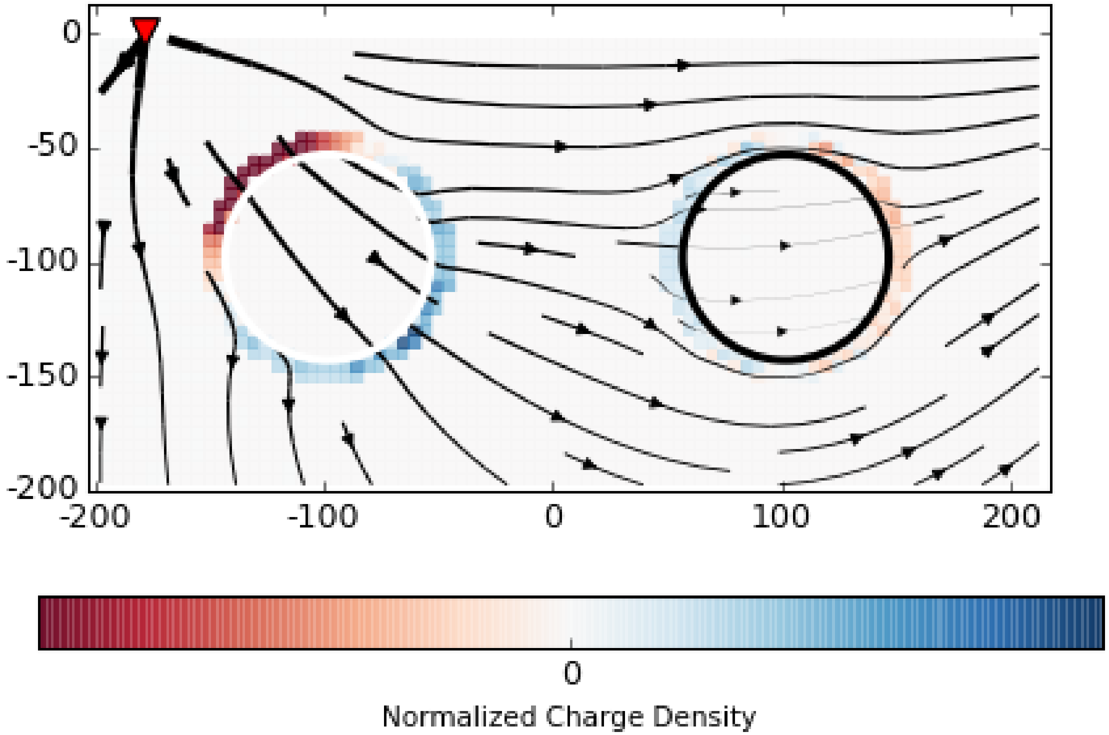
$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



Images generated using DC_Plate2_5D.ipynb. A: -30.25 m, B: 30.25 m, M: -10.25 m, N = 10.25 m. $\rho 1$ = 500 Ω·m, $\rho 2$ = 5000 Ω·m. dx = 10, dz=20, xc = 0, zc = -20, theta = 21.

Test

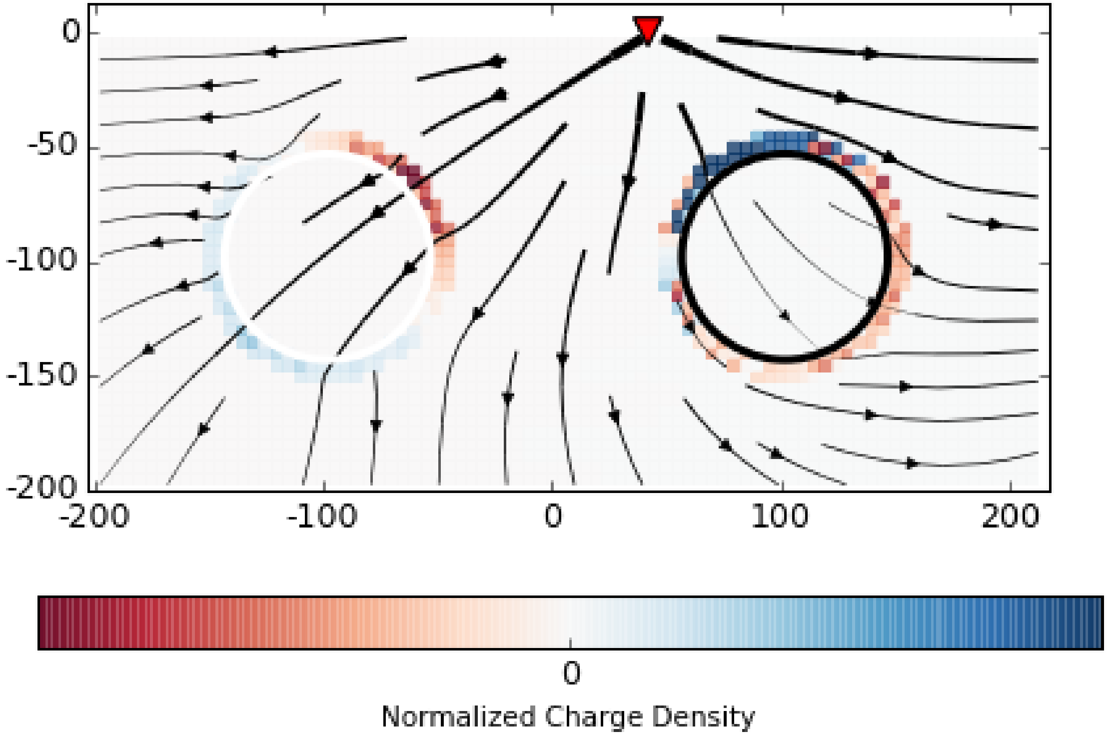
Can you tell which one is conductive and which one is resistive?



https://gpg.geosci.xyz/content/DC_resistivity/DC_basic_principles_heterogeneous_earth.html

Test

Now that you have figured out which one is conductive and which is resistive. What do you think the charges will look like for the following scenario?



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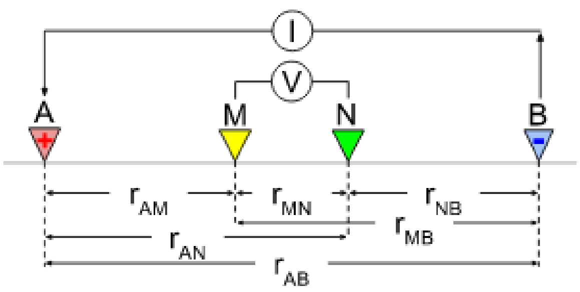
Currents and Apparent Resistivity

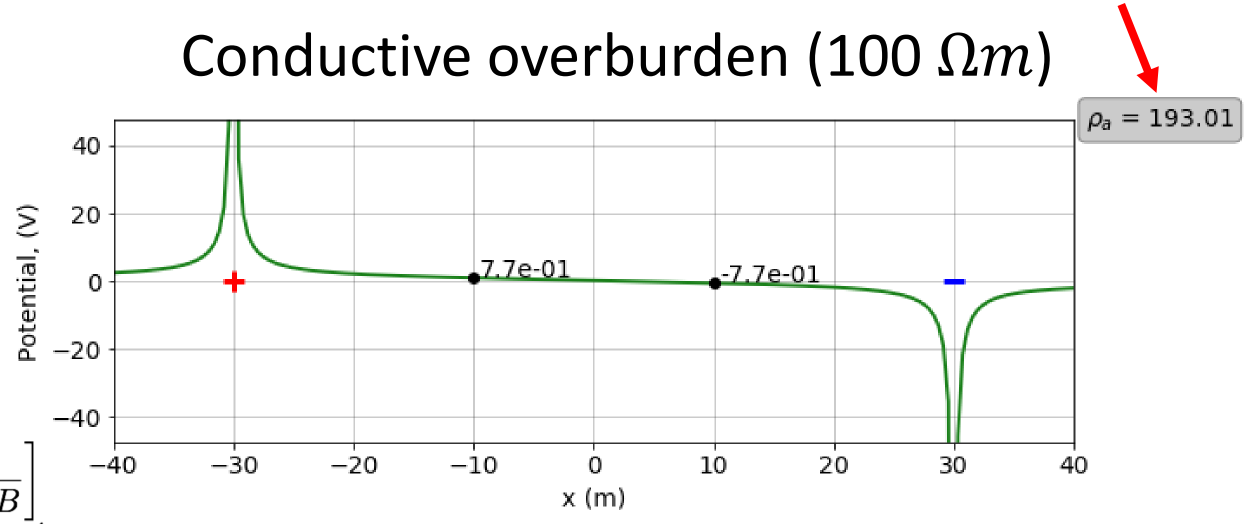


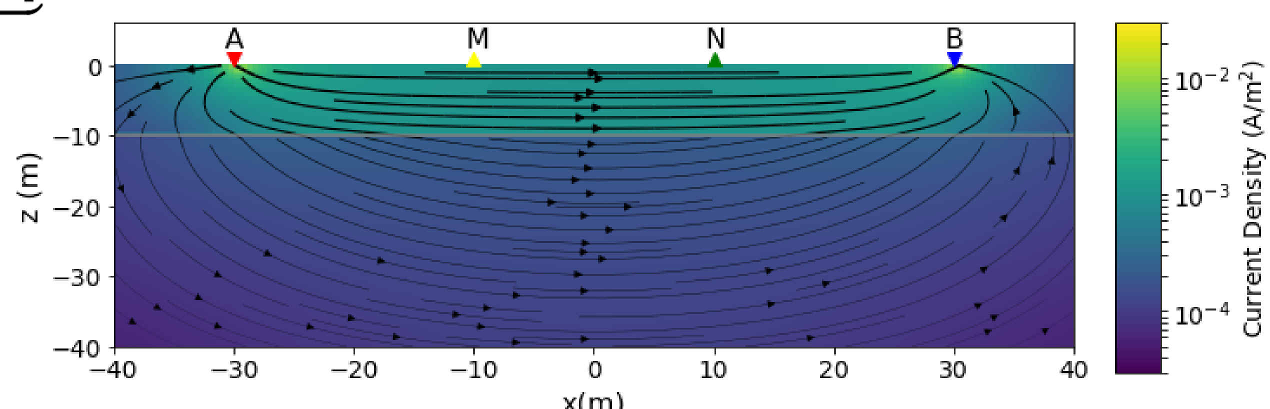
$$\Delta V_{MN} = \rho I \underbrace{\frac{1}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]}_{G}$$

Apparent resistivity

$$\rho_a = \frac{\Delta V_{MN}}{IG}$$

Conductive overburden (100 Ωm)





Images generated using DC_Layered Earth.ipynb. A: -30 m, B: 30 m, M: -10 m, N = 10 m. $\rho 1$ = 100 Ω·m, $\rho 2$ = 500 Ω·m. h = 10 m.

Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Apparent resistivity

$$\rho_a = \frac{\Delta V_{MN}}{IG}$$

- If the Earth is homogeneous, the apparent resistivity is equal to the true resistivity of the Earth.
- For inhomogeneous Earth, the apparent resistivity is some complicated averaging of the resistivities of all materials encountered by the currents.

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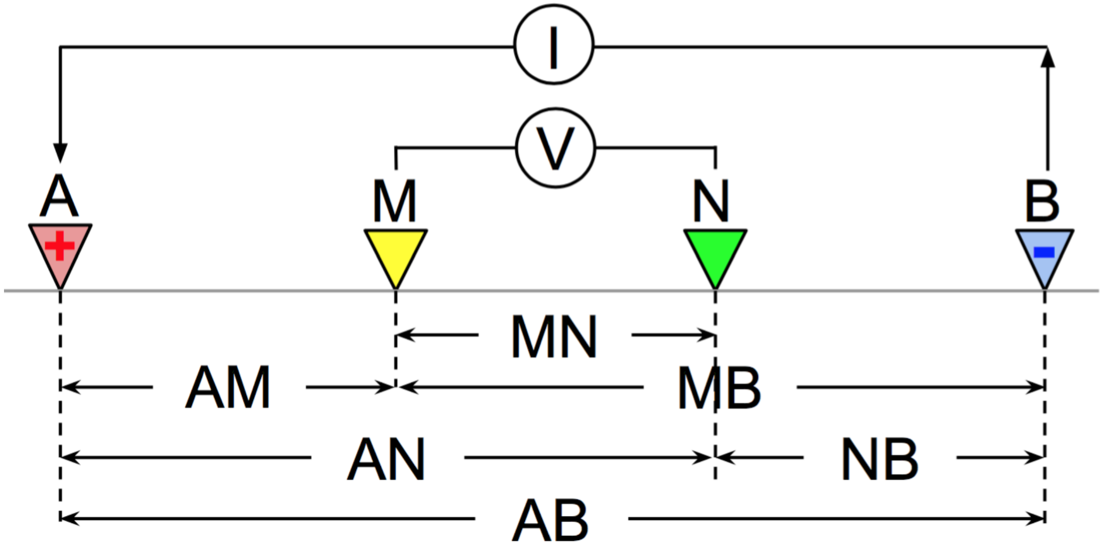
- If the Earth is homogeneous, the apparent resistivity is equal to the true resistivity of the Earth.

- For inhomogeneous Earth, the apparent resistivity is some complicated averaging of the resistivities of all materials encountered by the currents.

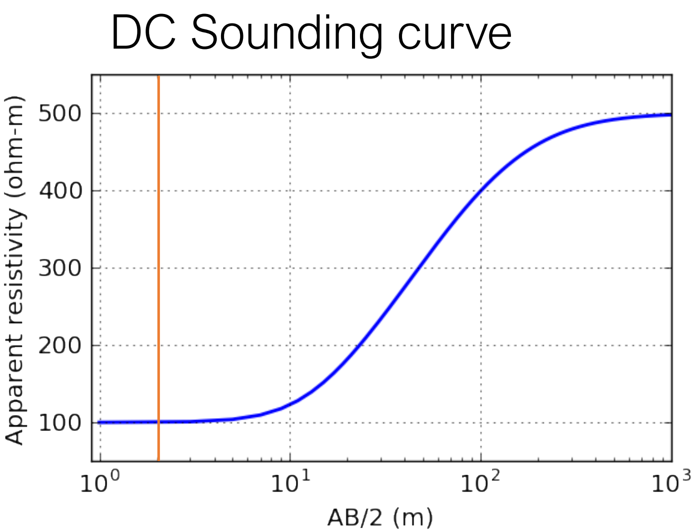
- It can be interpreted as the resistivity that would have been measured if the Earth were homogeneous.

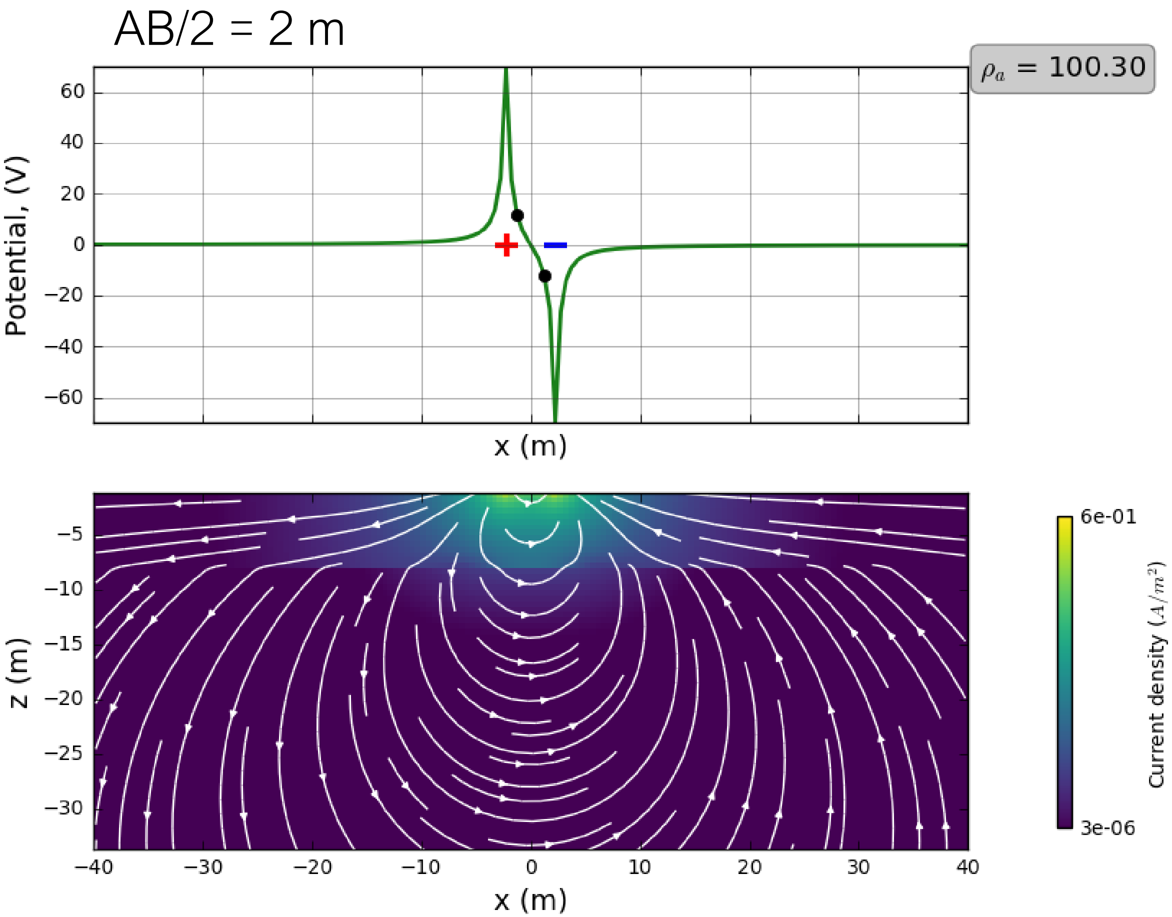
Sounding

- Keep the distance between M and N fixed
- Expand A and B



Sounding





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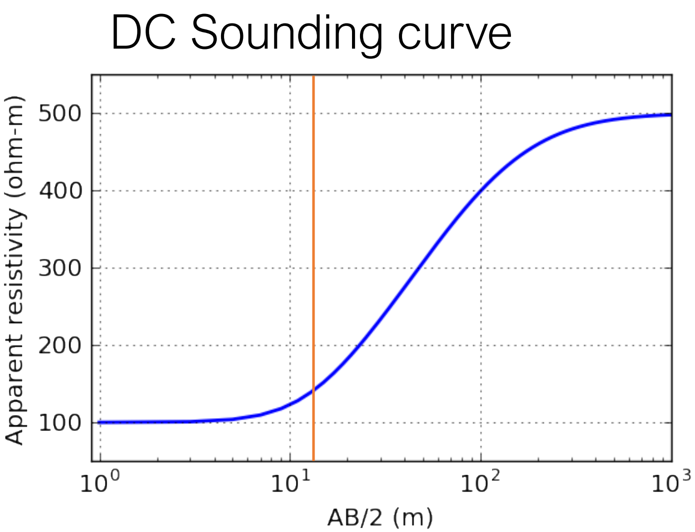

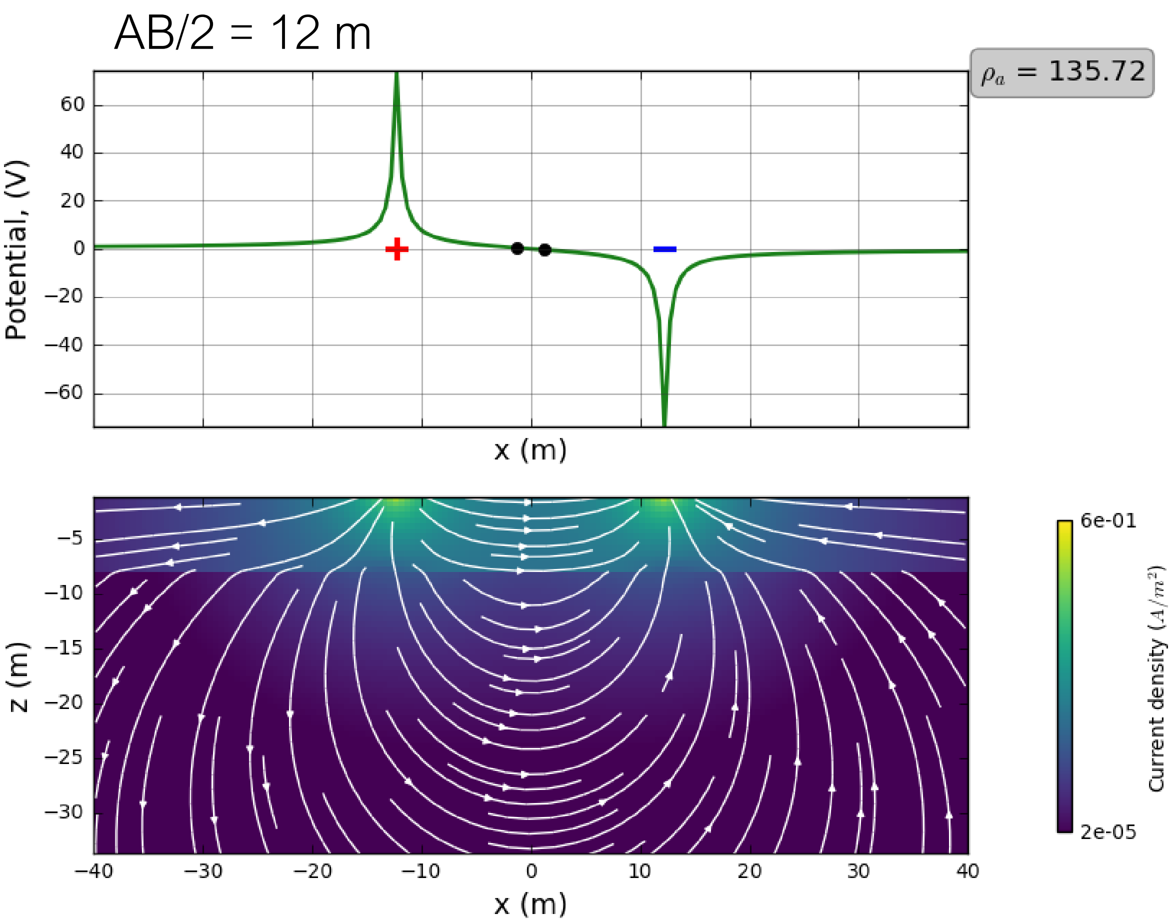

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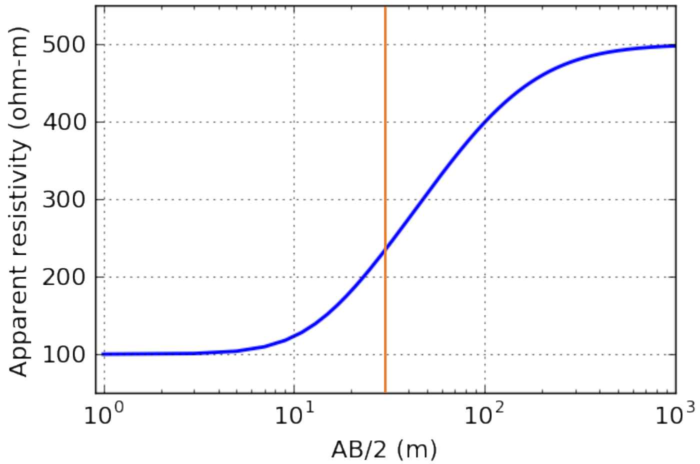
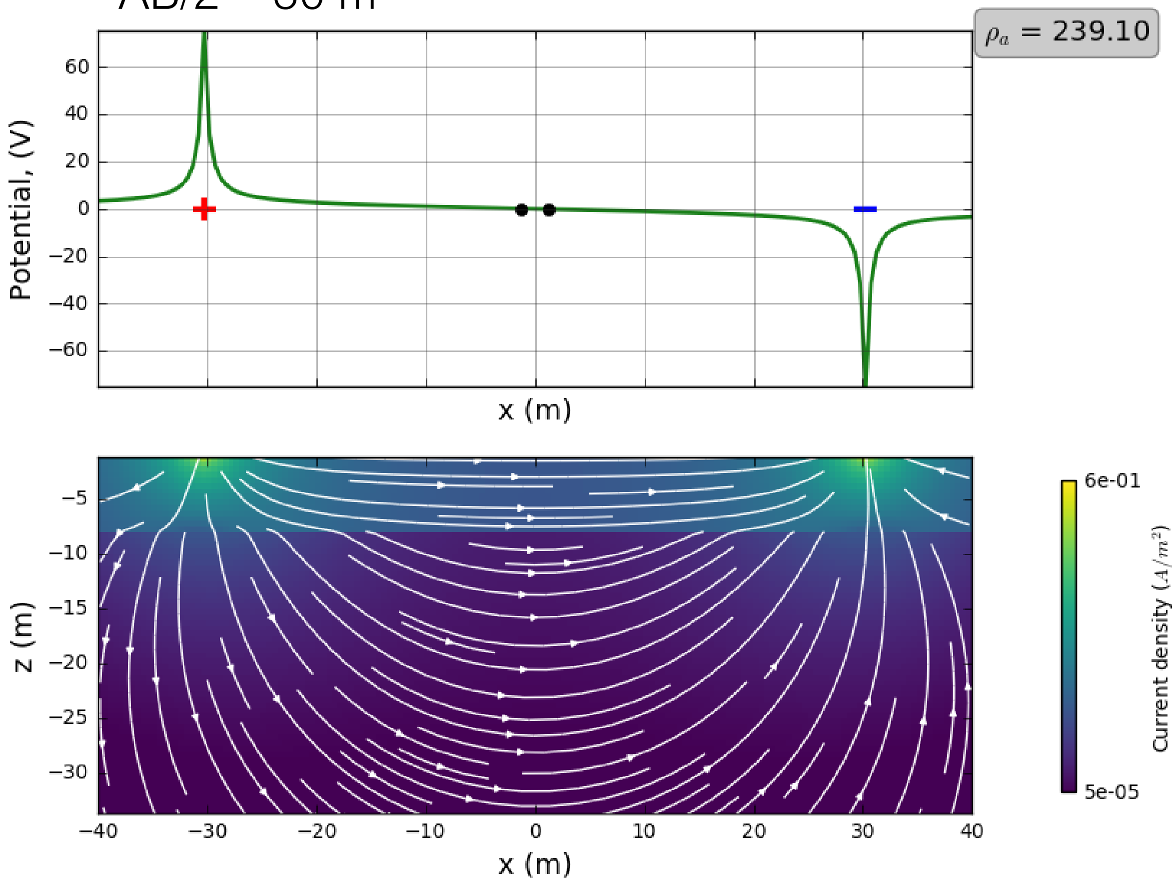
Sounding

DC Sounding curve



AB/2 = 30 m



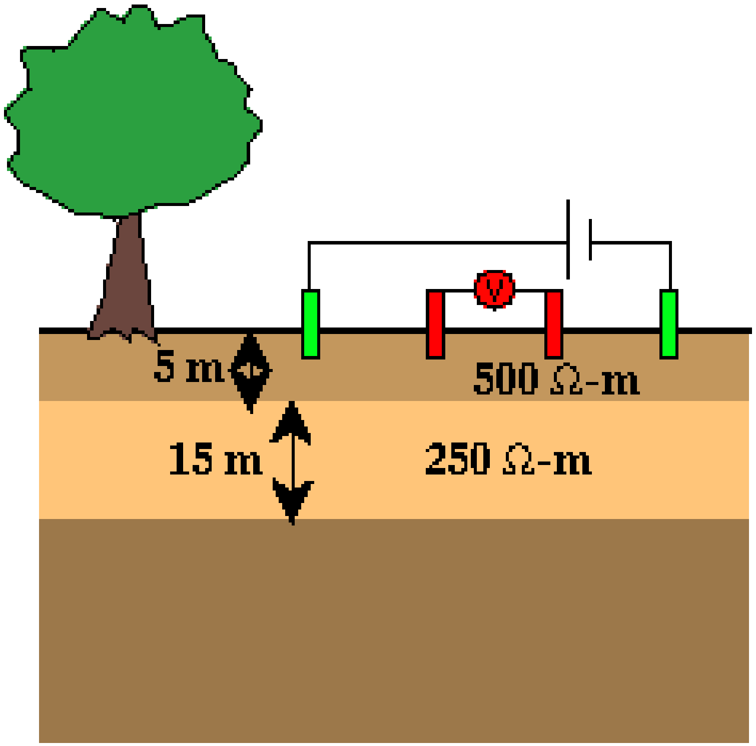
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

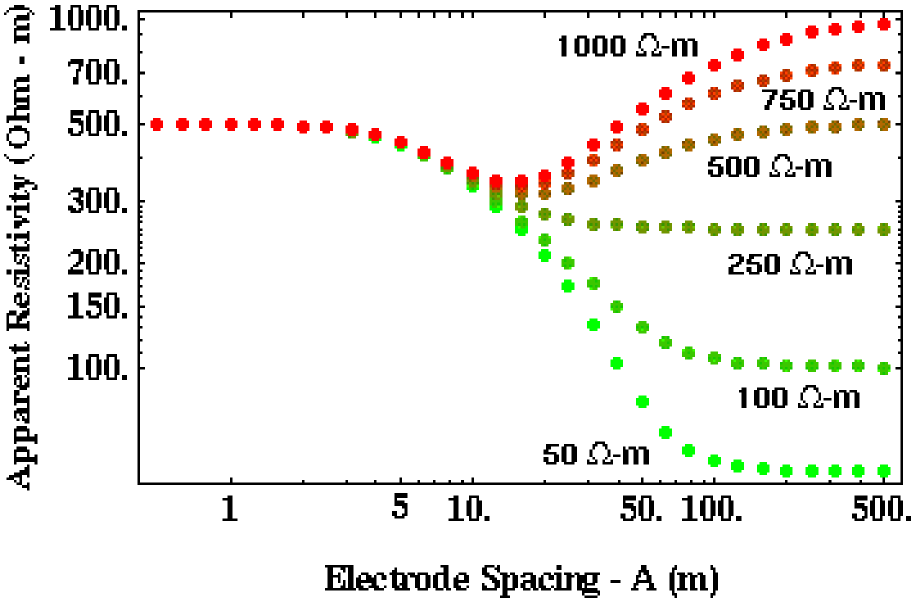
Observations:

- At small electrode spacings current flows only in near-surface regions. Apparent resistivities look similar to the true resistivity of overburden.
- As current flows deeper, apparent resistivities are influenced by the true resistivities of deeper materials.
- The sounding curve begins to indicate that there are at least 2 layers under this location.
- At very large electrode spacings most of the information reflects deeper ground because that is where most of the current is flowing.

https://em.geosci.xyz/content/geophysical_surveys/dcr/data.html

A three-layer model

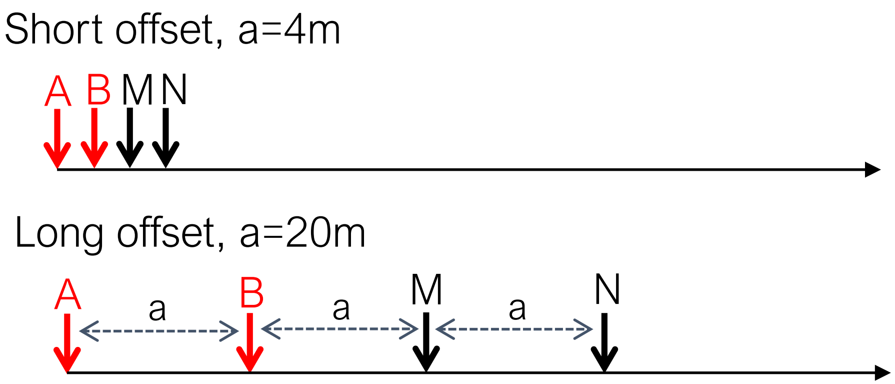


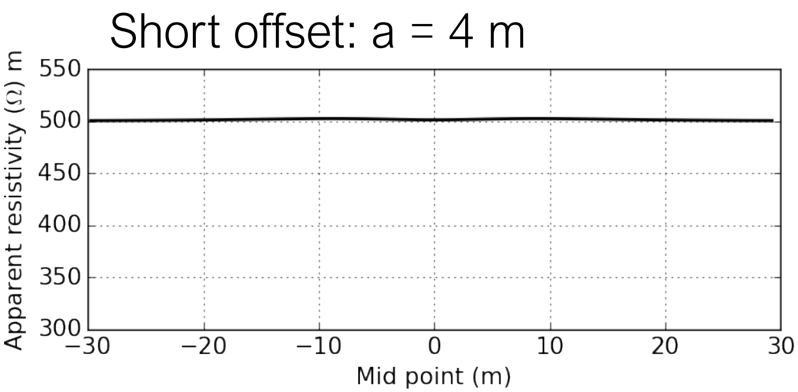


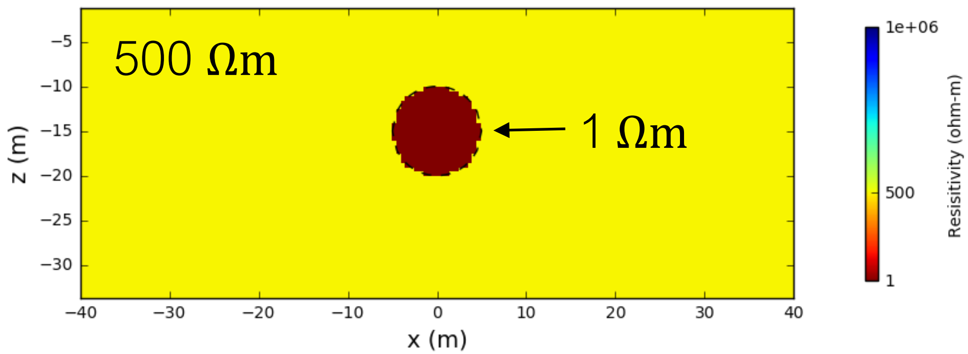
For mode discussions on the sounding curves:
https://pburnley.faculty.unlv.edu/GEOL442_642/RES/NOTES/ResistivityNotes25MLayer1.html

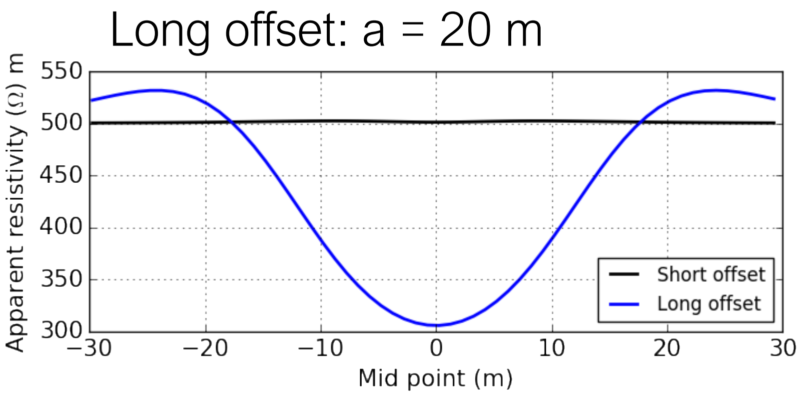
Profiling

Fixed geometry: Move laterally









Depth of investigation depends upon offset or array length

Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Summary: Profiling

- An array with fixed geometry (or, configuration) is moved along a line
- The data provide information about lateral variations of the Earth's resistivity up to a depth that is determined by the length of the array

DC Resistivity

- Understanding the secondary charges that are built up on the boundaries of anomalous bodies
- Understanding apparent resistivity (an average measure of the subsurface resistivities)
- Understanding sounding and profiling
- Being able to interpret the sounding and profiling curves
- Understanding the shielding problem in DC resistivity survey

“shielding” problem

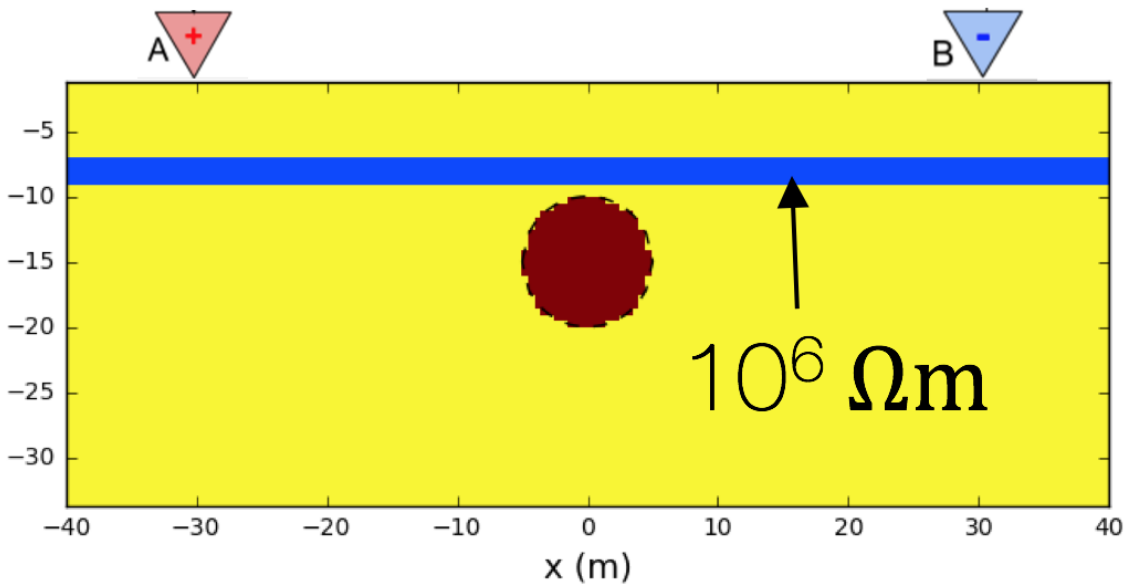
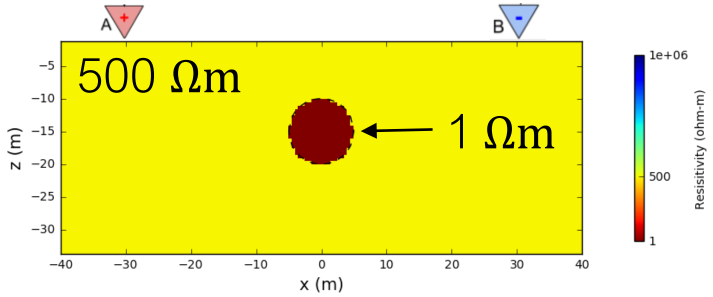


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

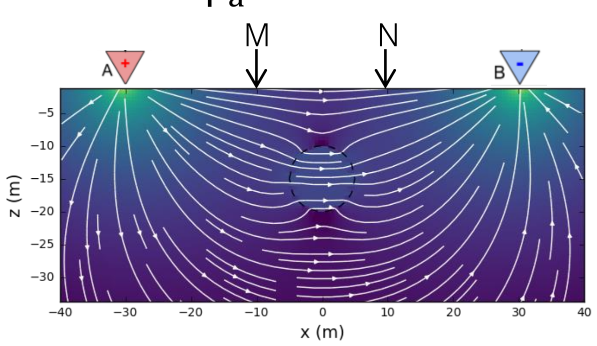
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

ρ_a = 430 Ωm



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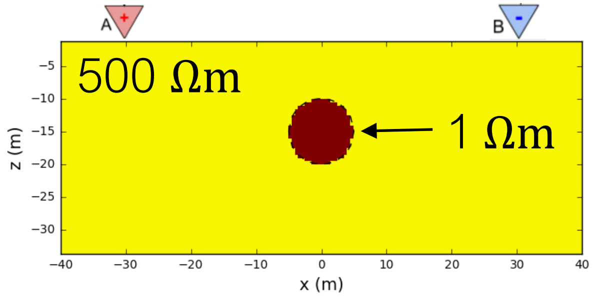

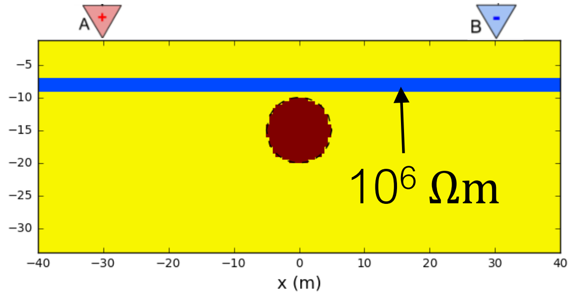

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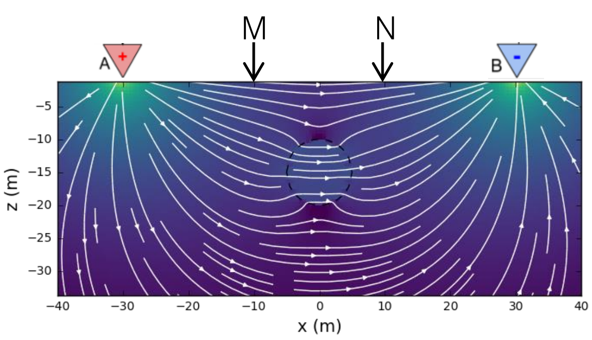

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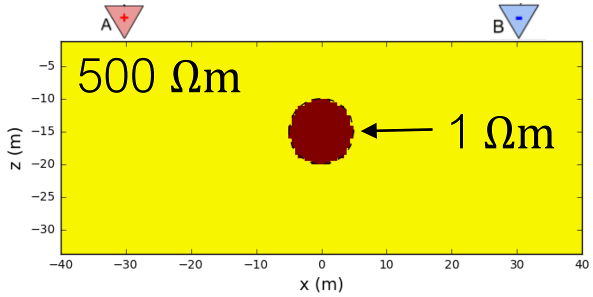
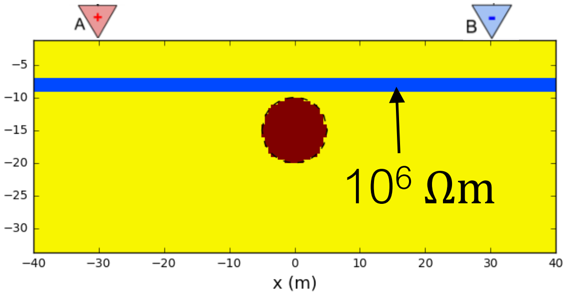
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)





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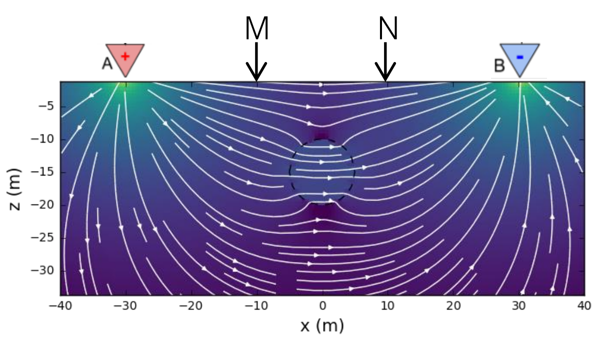
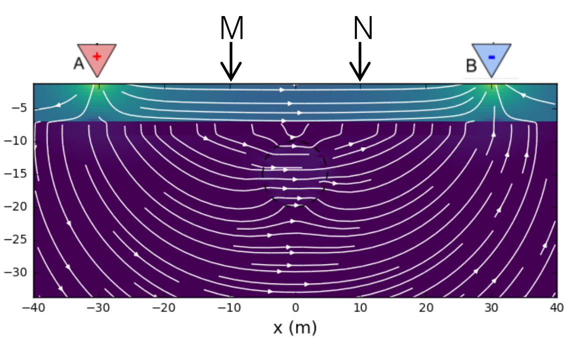


ρ_a = 1652 Ωm



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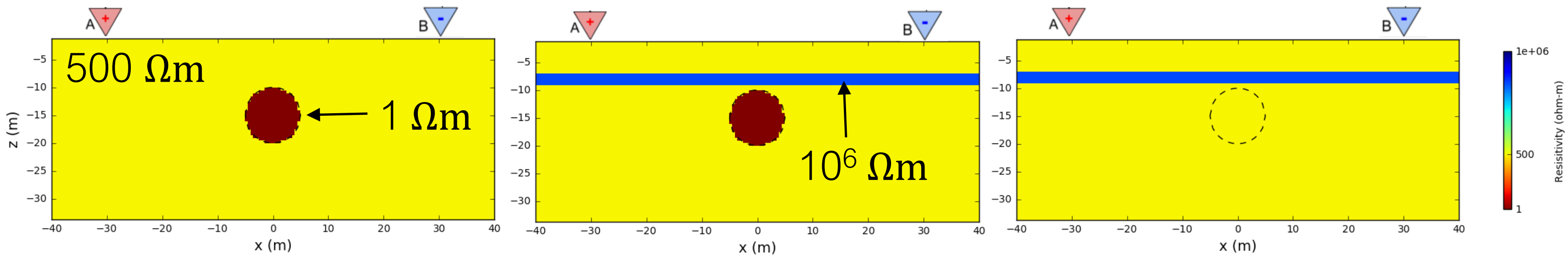
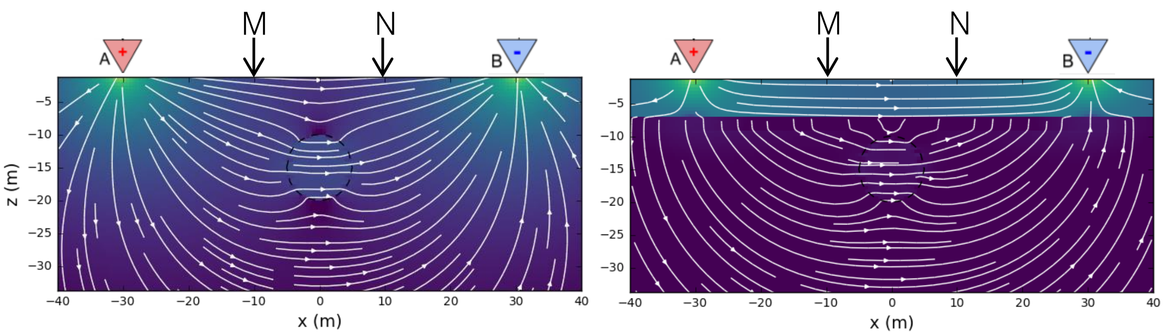
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

ρ_a = 430 Ωm ρ_a = 1652 Ωm



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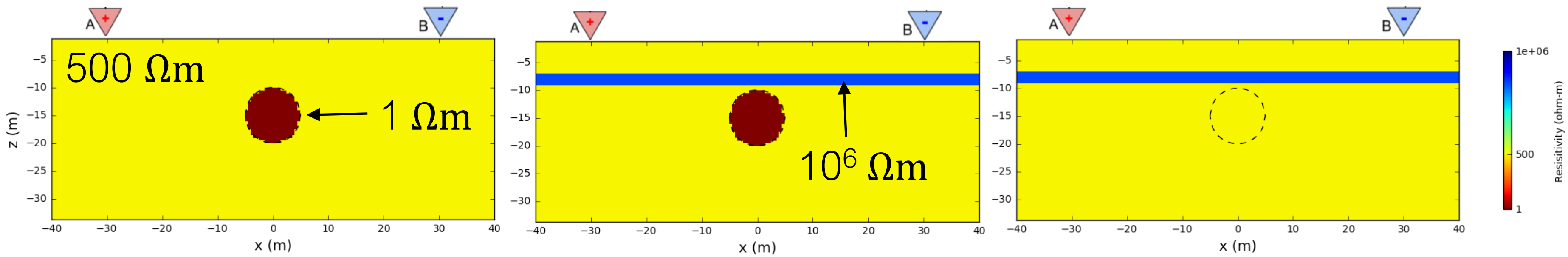
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

ρ_a = 430 Ωm ρ_a = 1652 Ωm ρ_a = 1654 Ωm

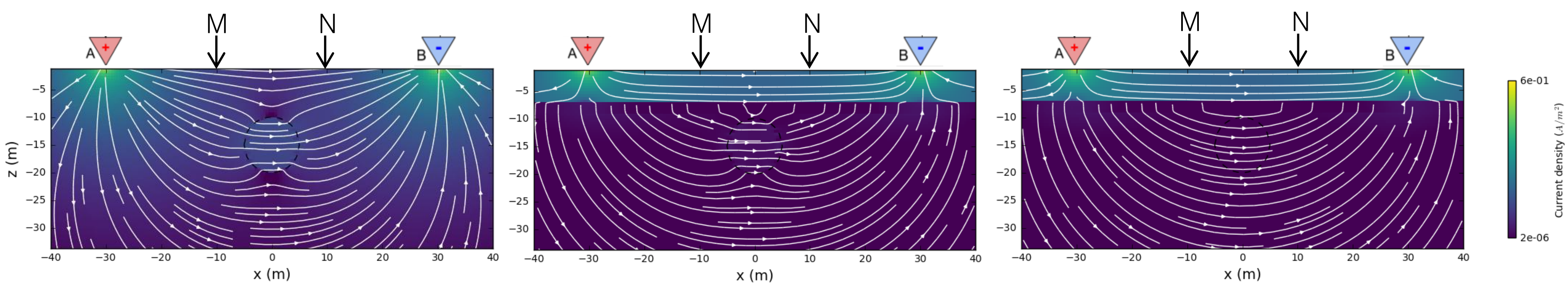


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Agenda

- DC resistivity
- RL circuit
- Plane waves
- Inductive source EM
- Grounded source EM

RL circuit

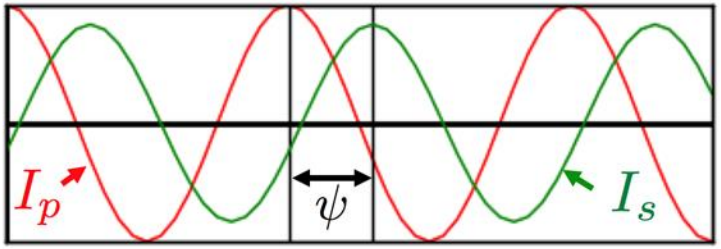
- Understanding frequency domain EM using RL circuit model
  - Understanding response function
  - Understanding in-phase vs. out-of-phase components
  - Interpreting frequency-domain EM measurements
- Understanding time domain EM using RL circuit
  - Understanding the decay curves (how resistivities affect the decay of EM response)
  - Able to interpret time-domain EM measurements

In-phase vs out-of-phase

- Suppose we have two waveforms

$$I_p(t) = I_p \cos \omega t$$

$$I_s(t) = I_s \cos(\omega t - \psi)$$



- Let us decompose $I_s(t)$ into two parts

$$\begin{aligned} I_s(t) &= I_s \cos(\omega t - \psi) \\ &= \underbrace{I_s \cos\psi}_{\substack{\text{In-Phase} \\ \text{Real}}} \cos \omega t + \underbrace{I_s \sin\psi}_{\substack{\text{Out-of-Phase} \\ \text{Quadrature} \\ \text{Imaginary}}} \sin \omega t \end{aligned}$$

In-phase vs out-of-phase

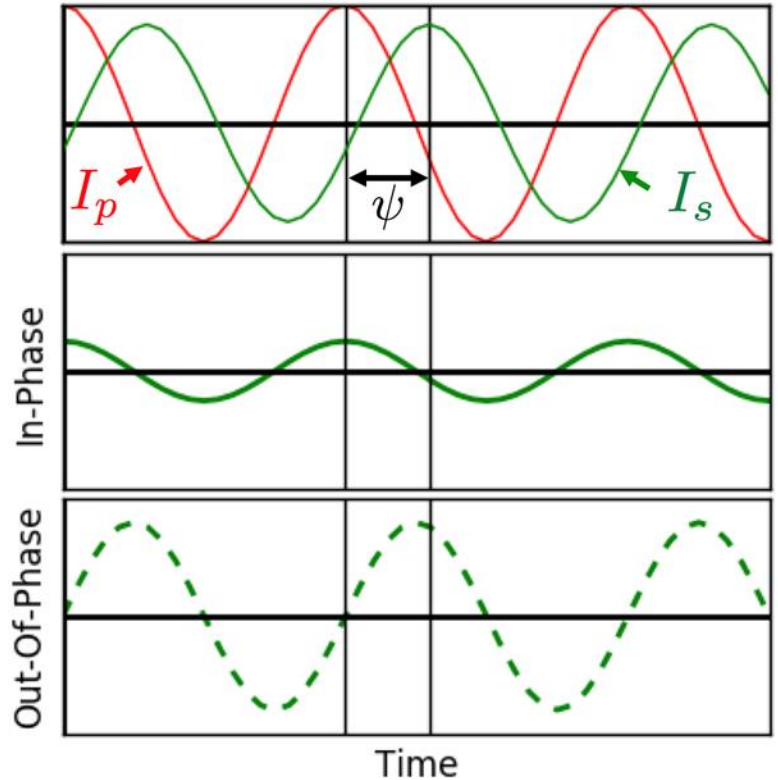
- Suppose we have two waveforms

$$I_p(t) = I_p \cos \omega t$$

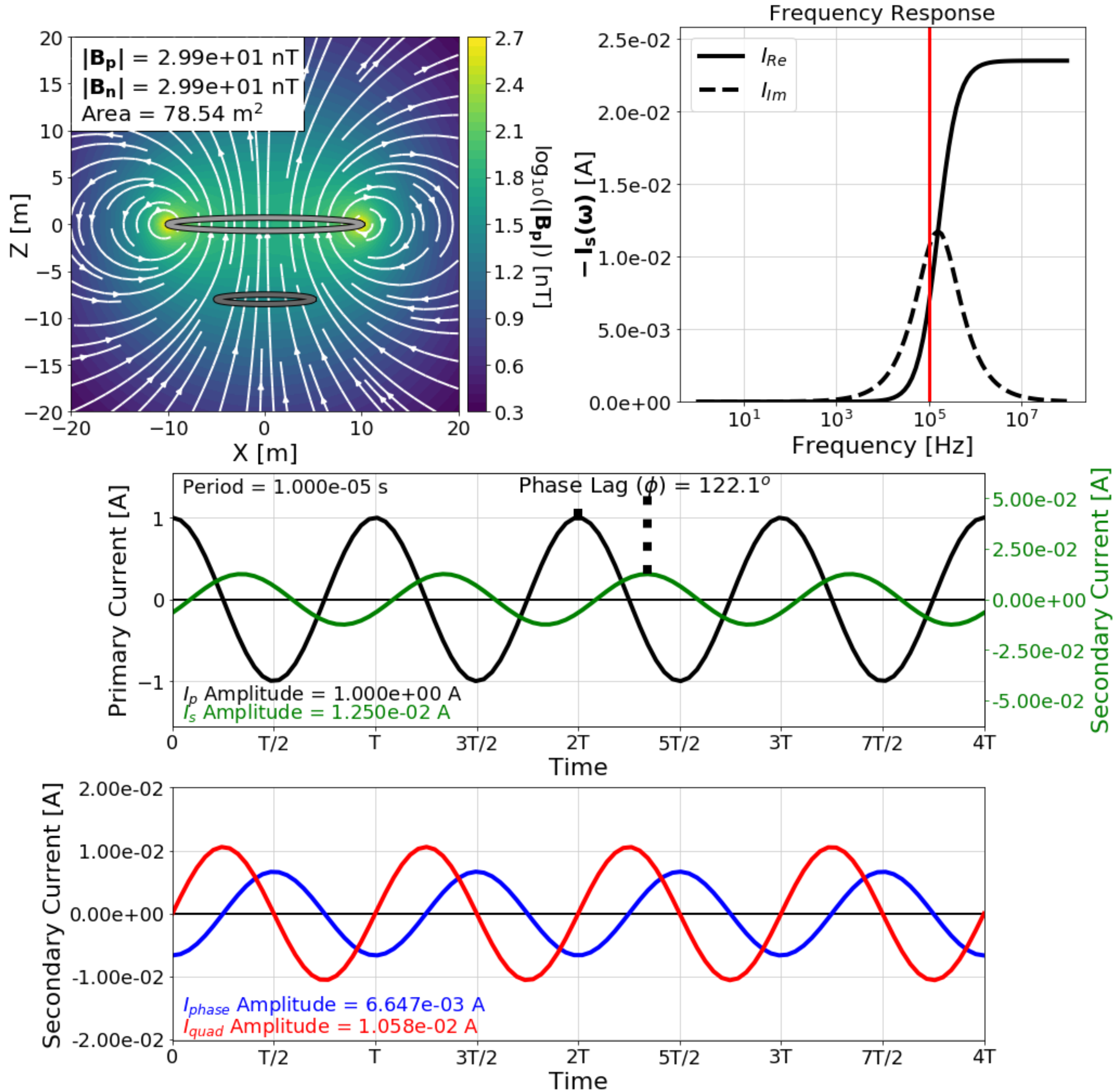
$$I_s(t) = I_s \cos(\omega t - \psi)$$

- Let us decompose $I_s(t)$ into two parts

$$I_s(t) = I_s \cos(\omega t - \psi)$$
$$= \underbrace{I_s \cos \psi}_{\substack{\text{In-Phase} \\ \text{Real}}} \cos \omega t + \underbrace{I_s \sin \psi}_{\substack{\text{Out-of-Phase} \\ \text{Quadrature} \\ \text{Imaginary}}} \sin \omega t$$



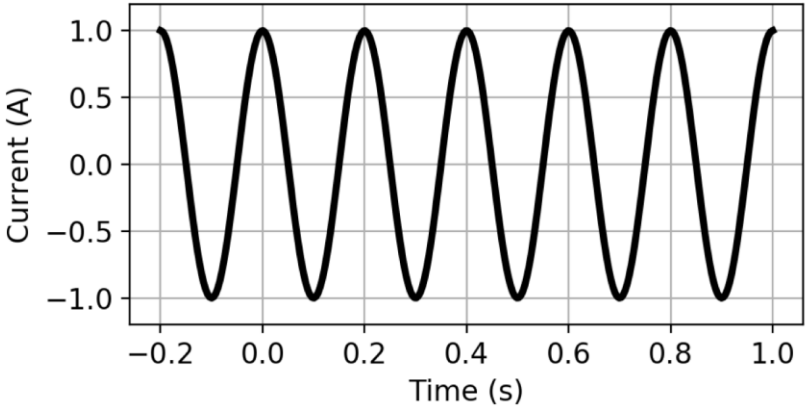
Therefore, $I_s(t)$, the green curve in upper panel, is the sum of in-phase component in the middle panel and the out-of-phase component in the bottom panel.



|Bp| = 2.99e+01 nT
|Bn| = 2.99e+01 nT
Area = 78.54 m²
Z [m]
X [m]
log10(|Bp|) [nT]
Frequency Response
I_Re
I_Im
−Is(ω) [A]
Frequency [Hz]
Period = 1.000e-05 s
Phase Lag (ϕ) = 122.1°
Primary Current [A]
Secondary Current [A]
Ip Amplitude = 1.000e+00 A
Is Amplitude = 1.250e-02 A
Time
Secondary Current [A]
Iphase Amplitude = 6.647e-03 A
Iquad Amplitude = 1.058e-02 A
Time

Frequency-domain EM response

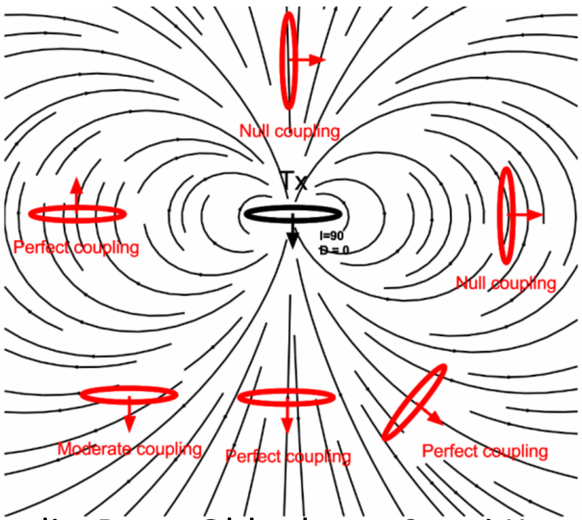
AC current in Tx



$$\frac{H_s^3}{H_p^3} = \frac{\varepsilon_3^s}{\varepsilon_3^p} = \boxed{-\frac{M_{12}M_{23}}{M_{13}L}}\boxed{\frac{\alpha^2 + i\alpha}{1+\alpha^2}}$$

Coupling coefficient

Response function



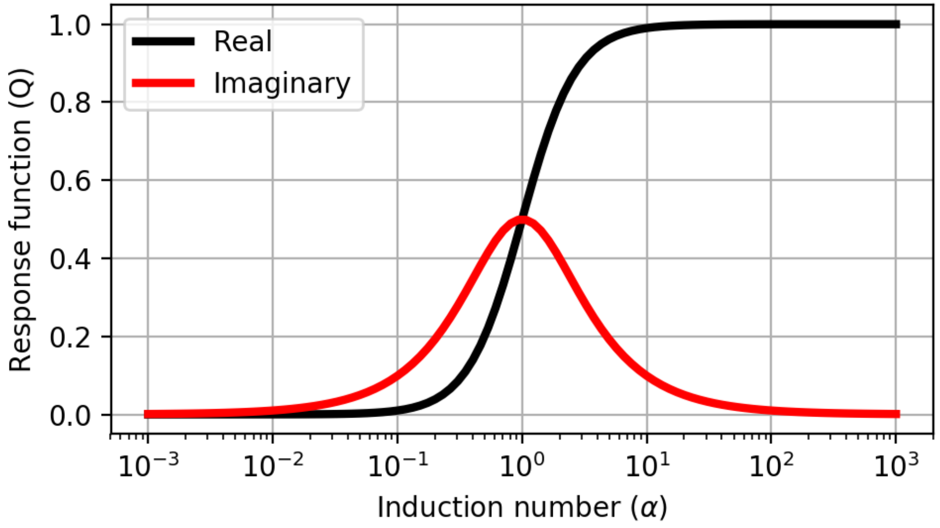


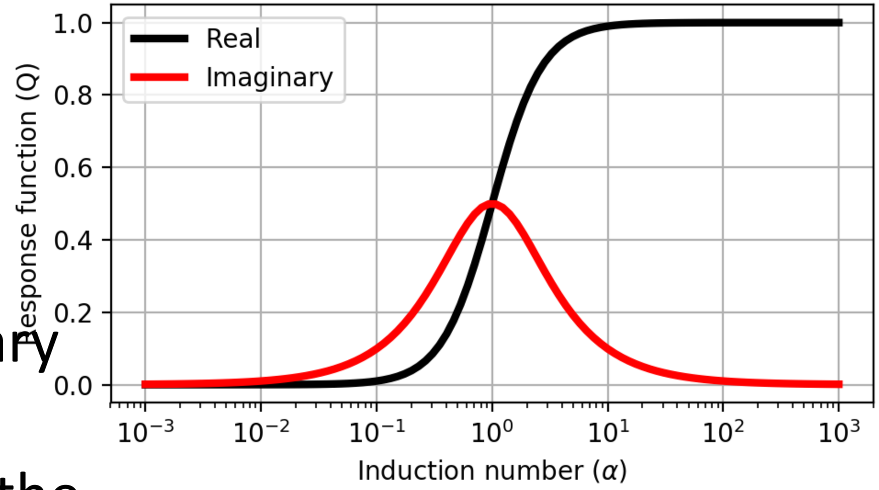
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Understanding the response function

$$Q = \frac{\alpha^2 + i\alpha}{1+\alpha^2} \quad \text{with } \alpha = \frac{wL}{R}$$

when $\alpha \ll 1$

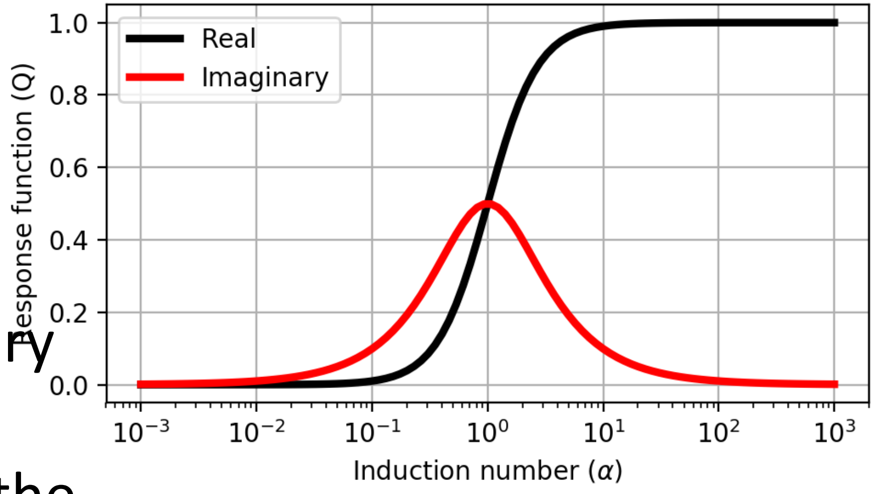
$$Q \approx i\alpha$$



- The EM response is purely imaginary and small.
- The amount of current induced in the body will also be small. Remember that $|I| = \frac{\varepsilon_2}{\sqrt{R^2 + w^2 L^2}}$

Understanding the response function

$$Q = \frac{\alpha^2 + i\alpha}{1+\alpha^2} \quad \text{with } \alpha = \frac{wL}{R}$$



Resistive limit: when $\alpha \ll 1$

$$Q \approx \; i\alpha$$

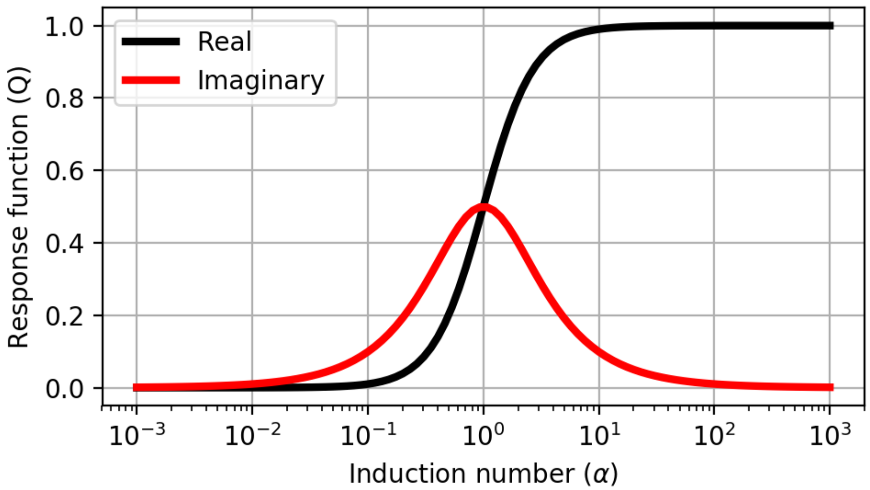
- The EM response is purely imaginary and small.
- The amount of current induced in the body will also be small. Remember that $|I| = \frac{\varepsilon_2}{\sqrt{R^2 + w^2 L^2}}$

Understanding the response function

$$Q = \frac{\alpha^2 + i\alpha}{1+\alpha^2} \quad \text{with } \alpha = \frac{wL}{R}$$

when $\alpha \gg 1$

$$Q \approx 1$$



- The EM response is largely real-valued.
- The imaginary part is very small.

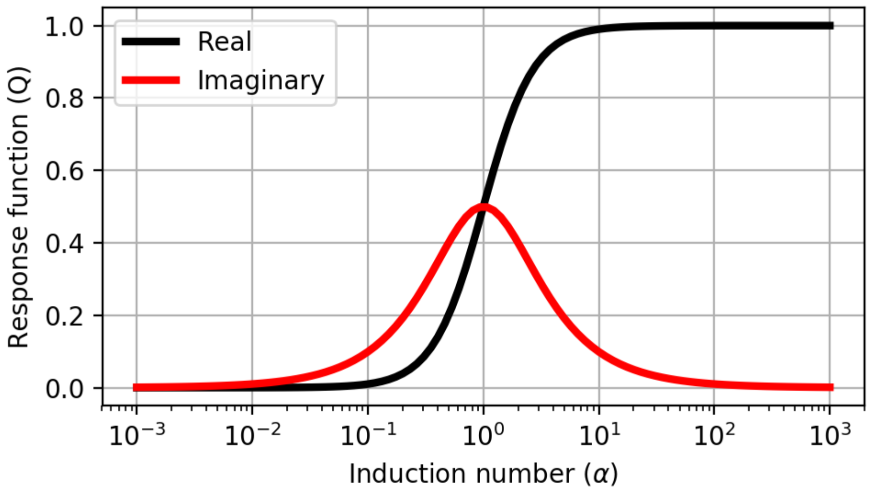
Understanding the response function

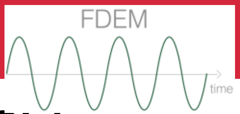
$$Q = \frac{\alpha^2 + i\alpha}{1+\alpha^2} \quad \text{with } \alpha = \frac{wL}{R}$$

Inductive limit: when $\alpha \gg 1$

$$Q \approx 1$$

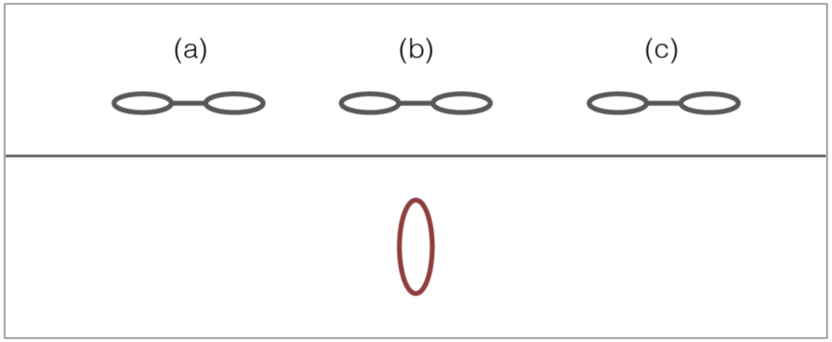
- The EM response is largely real-valued.
- The imaginary part is very small.

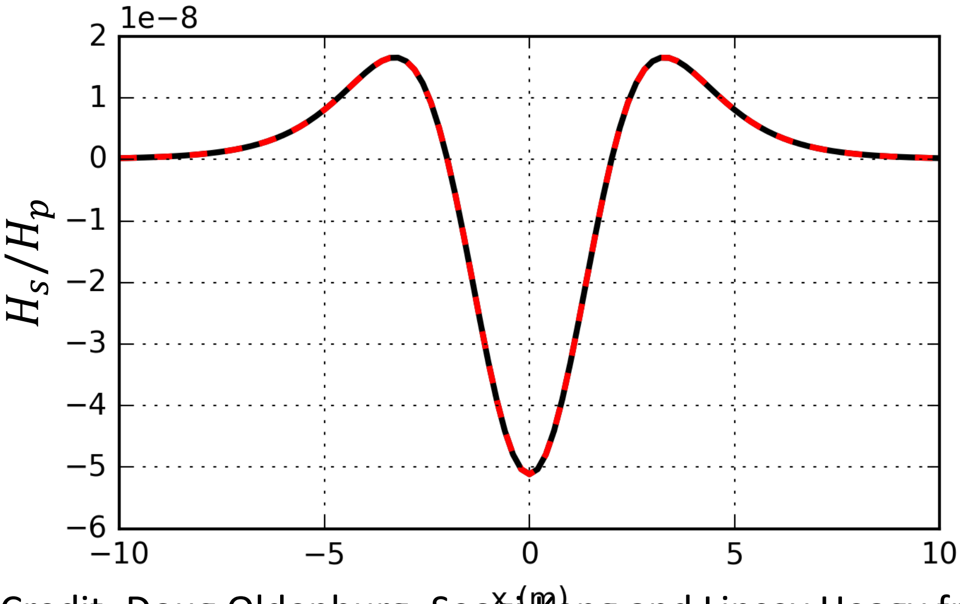




Conductor in a resistive earth: Frequency

Profile over the loop



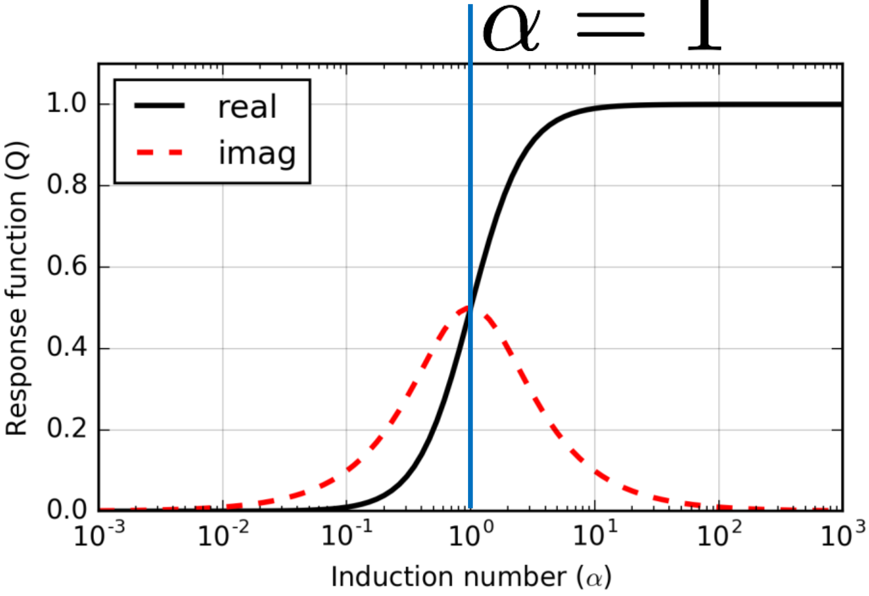


- Induction number

$$\alpha = \frac{\omega L}{R}$$

- When $\alpha = 1$
  - Real = Imag

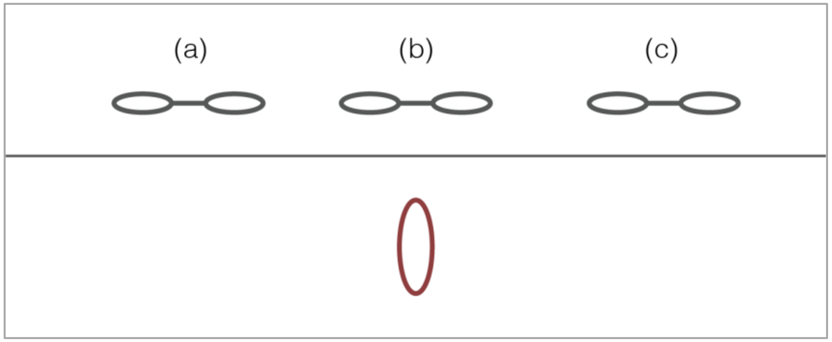
$\alpha = 1$



Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Conductor in a resistive earth: Frequency

Profile over the loop

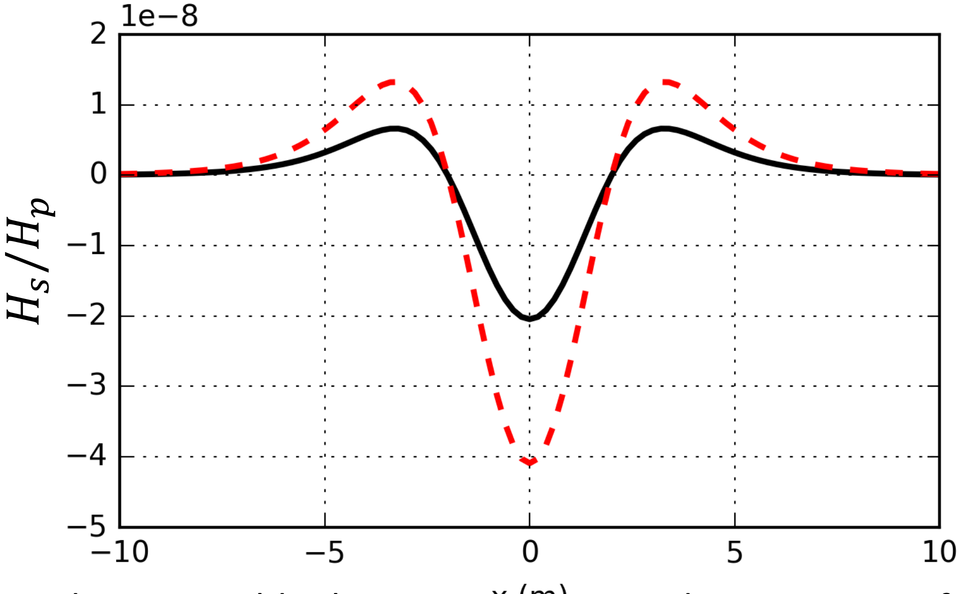


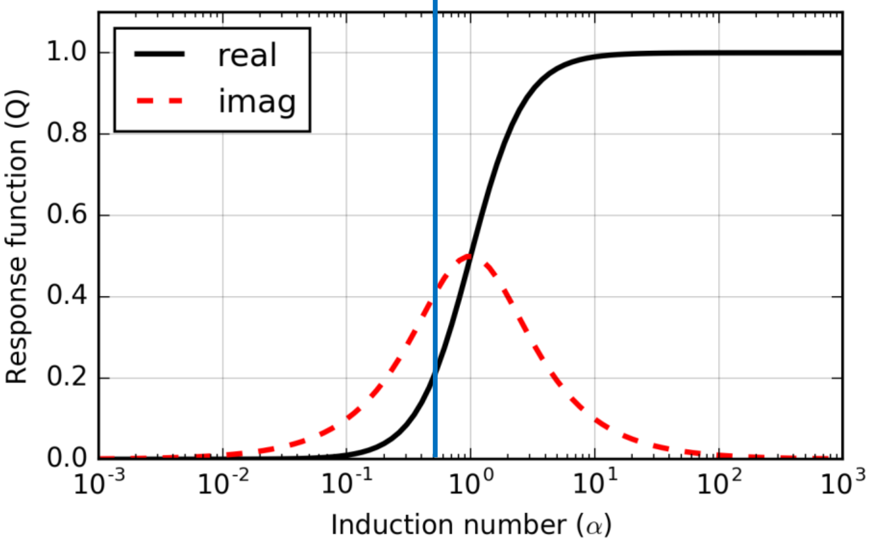
- Induction number

$$\alpha = \frac{\omega L}{R}$$

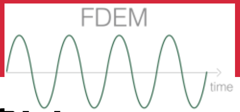
- When $\alpha < 1$
  - Real < Imag

$\alpha = 0.5$



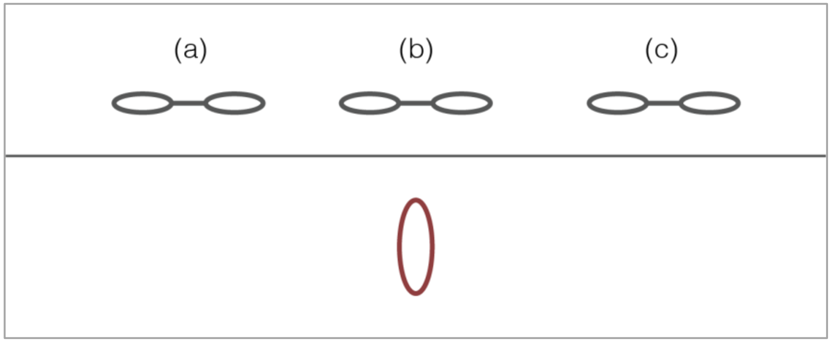


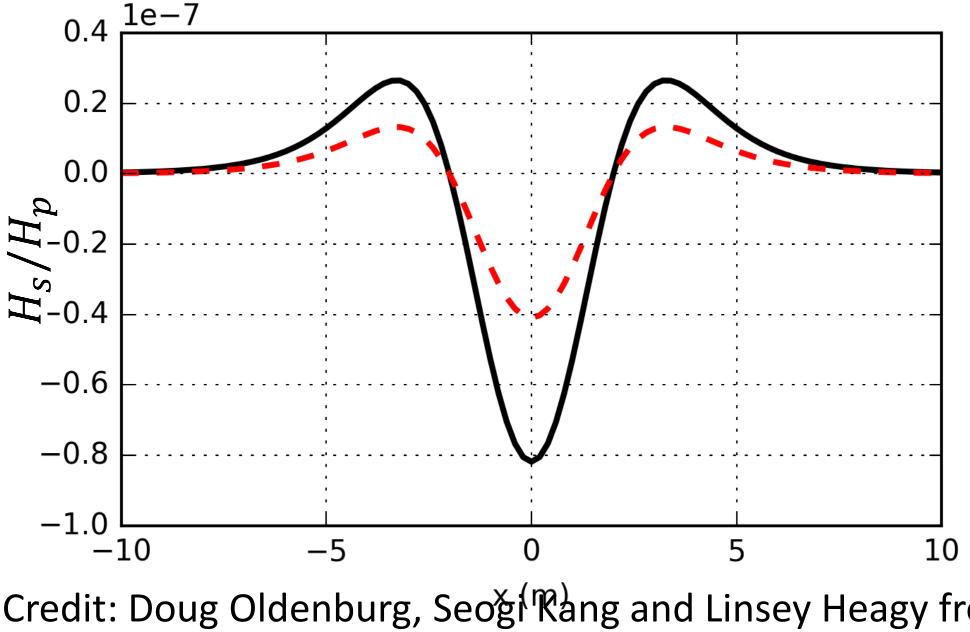
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF



Conductor in a resistive earth: Frequency

Profile over the loop



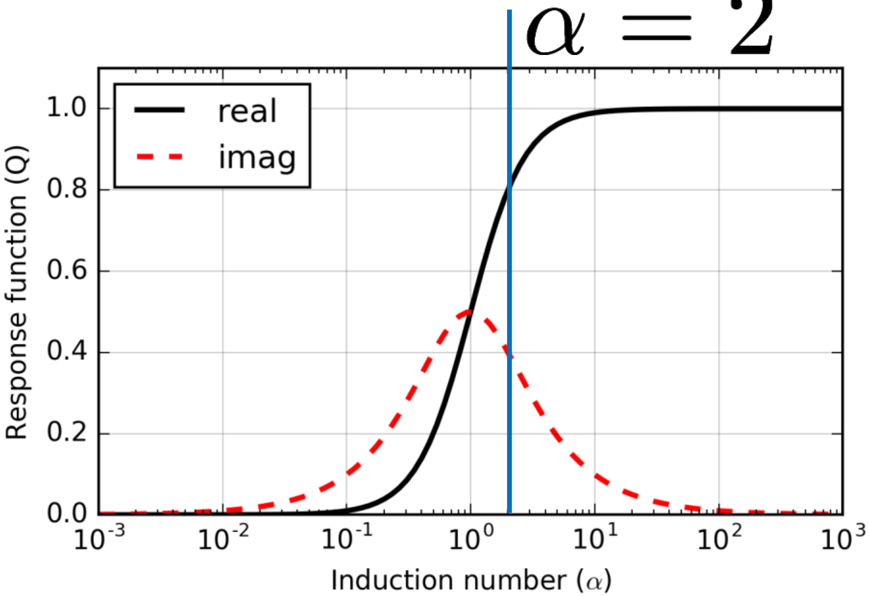


- Induction number

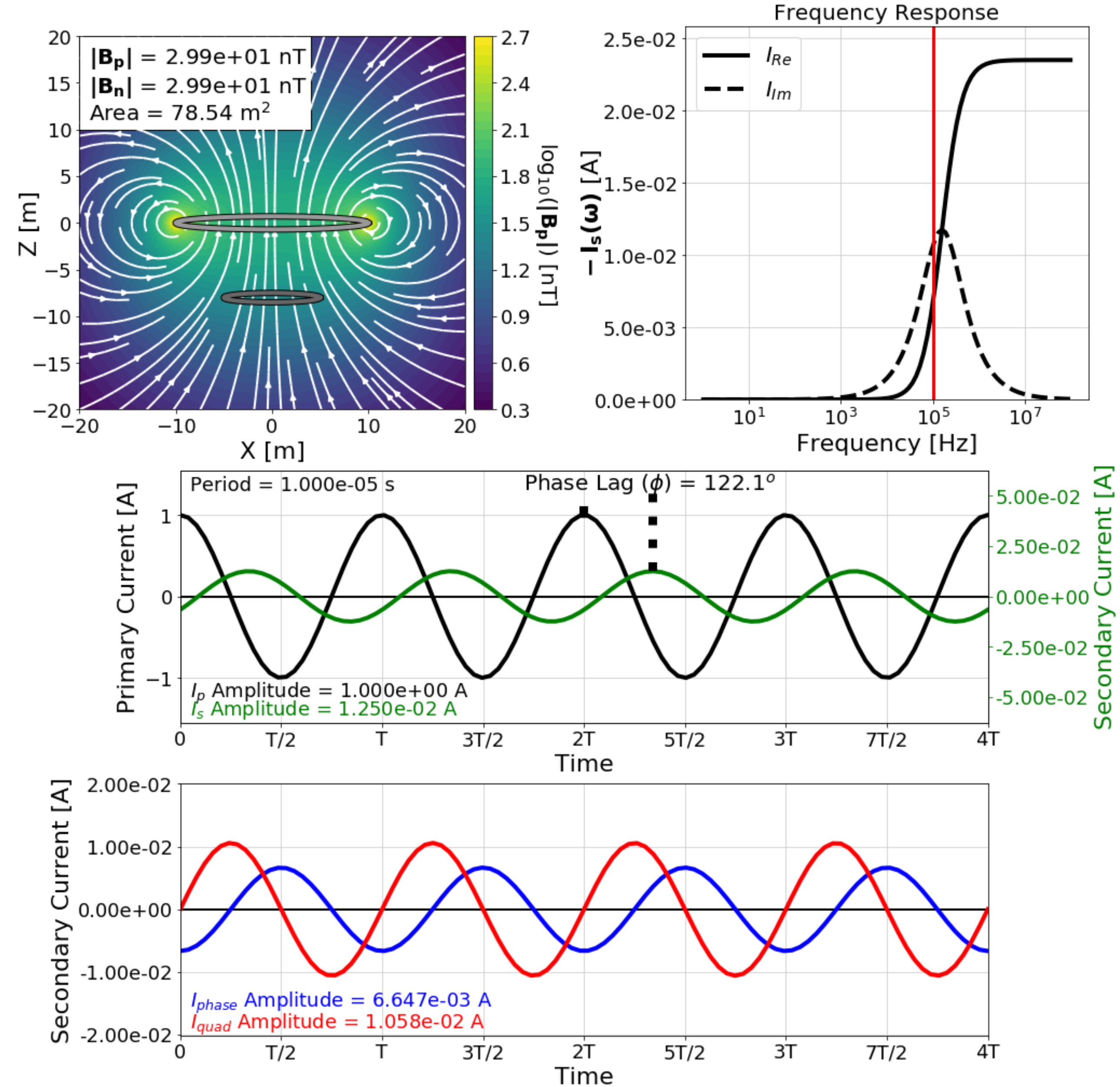
$$\alpha = \frac{\omega L}{R}$$

- When $\alpha > 1$
  - Real > Imag

$\alpha = 2$



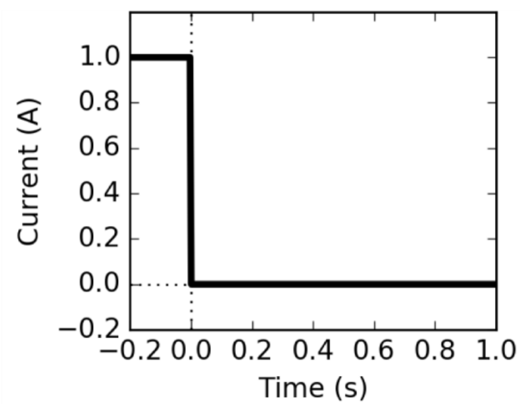
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF



Why is the in-phase component smaller than the out-of-phase component?

Time-domain EM response

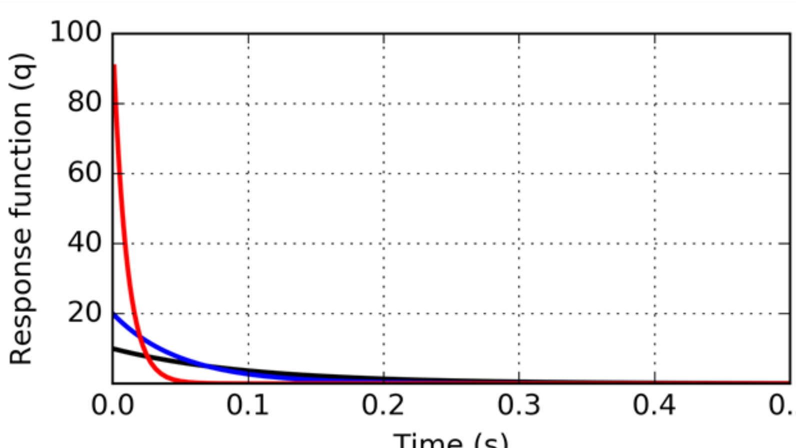
Step-off current in Tx



$$\varepsilon_3^s = \frac{M_{12}M_{23}}{L}\frac{I_1}{\tau}e^{-\frac{t}{\tau}}$$

where $\tau = \frac{L}{R}$, and $t > 0$

The larger the τ, the slower it decays. Therefore, the more conductive the subsurface, the slower it decays.



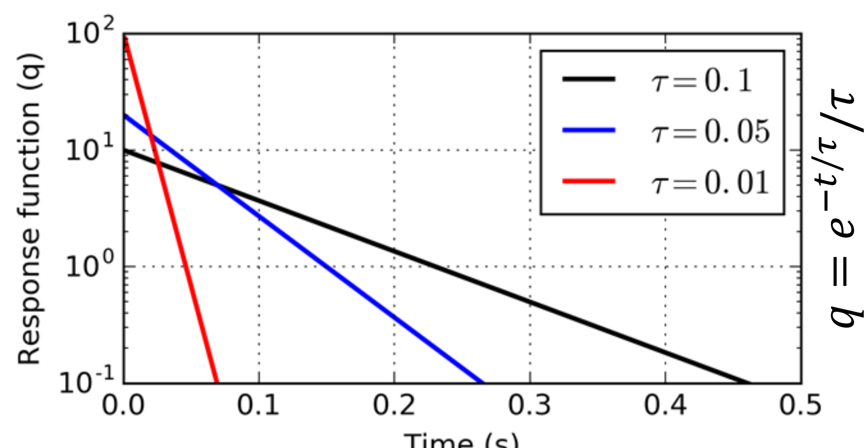
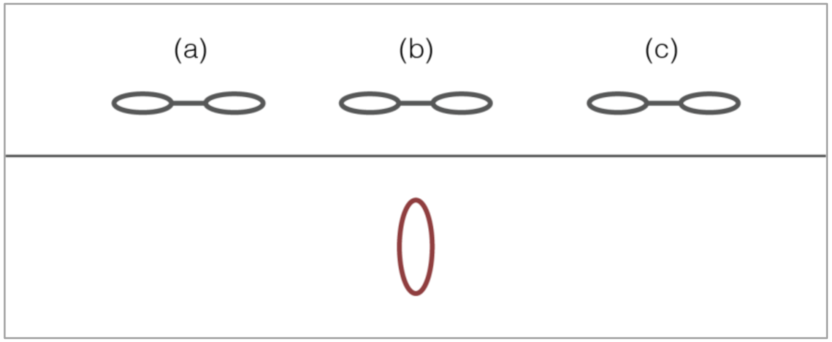
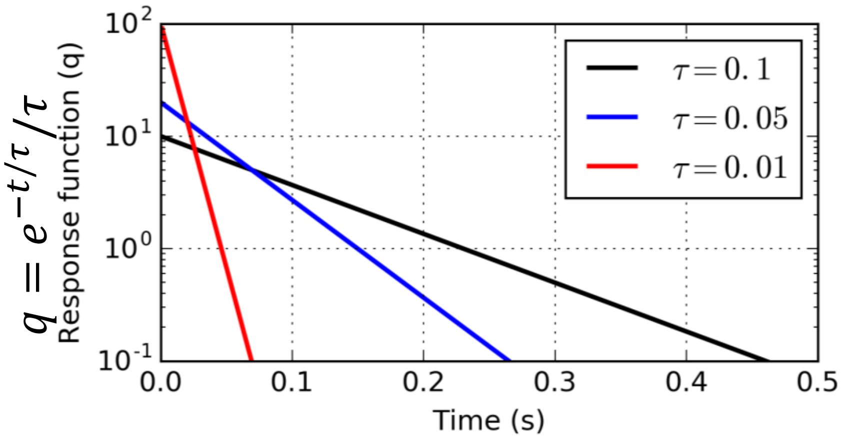


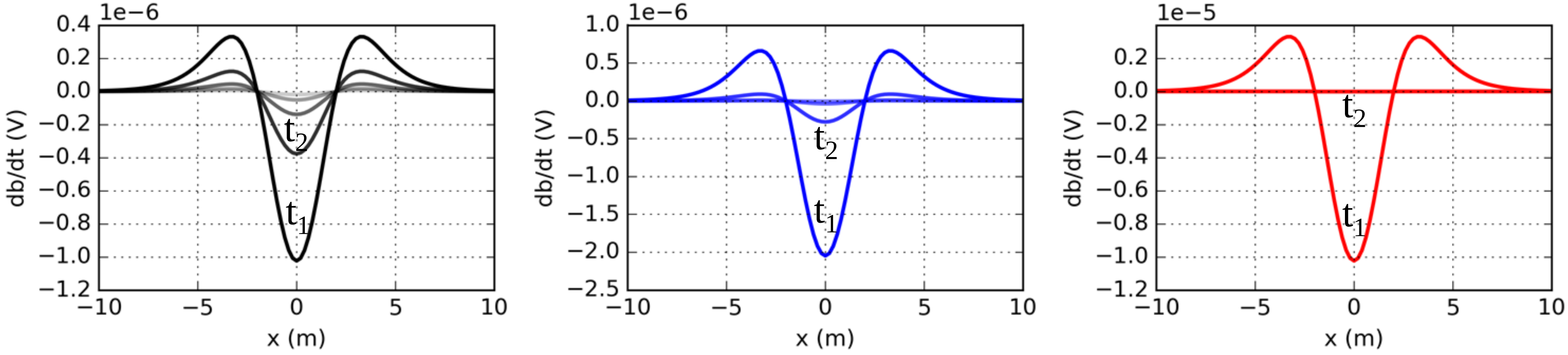
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Conductor in a resistive earth: Transient

Profile over the loop

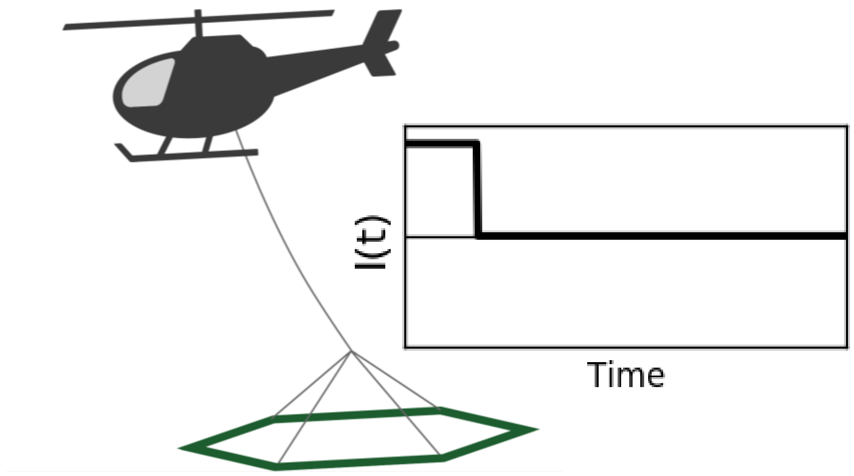




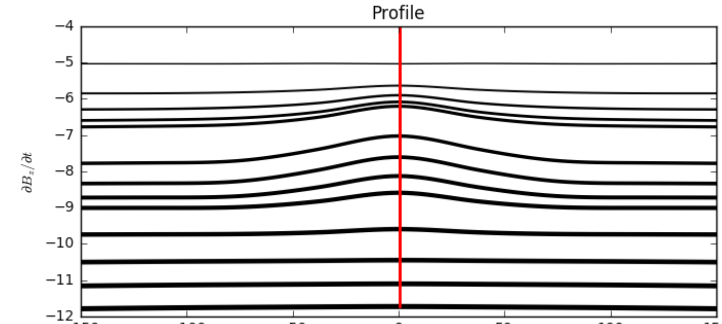


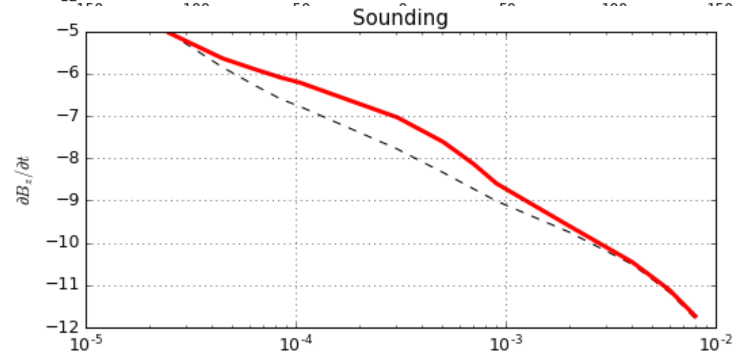
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

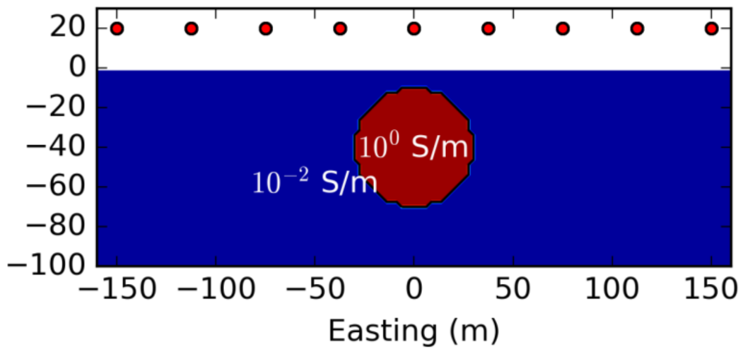
Synthetic airborne TEM data



Data profile







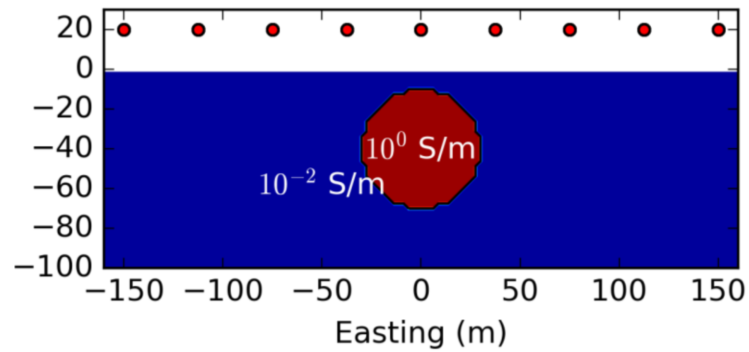
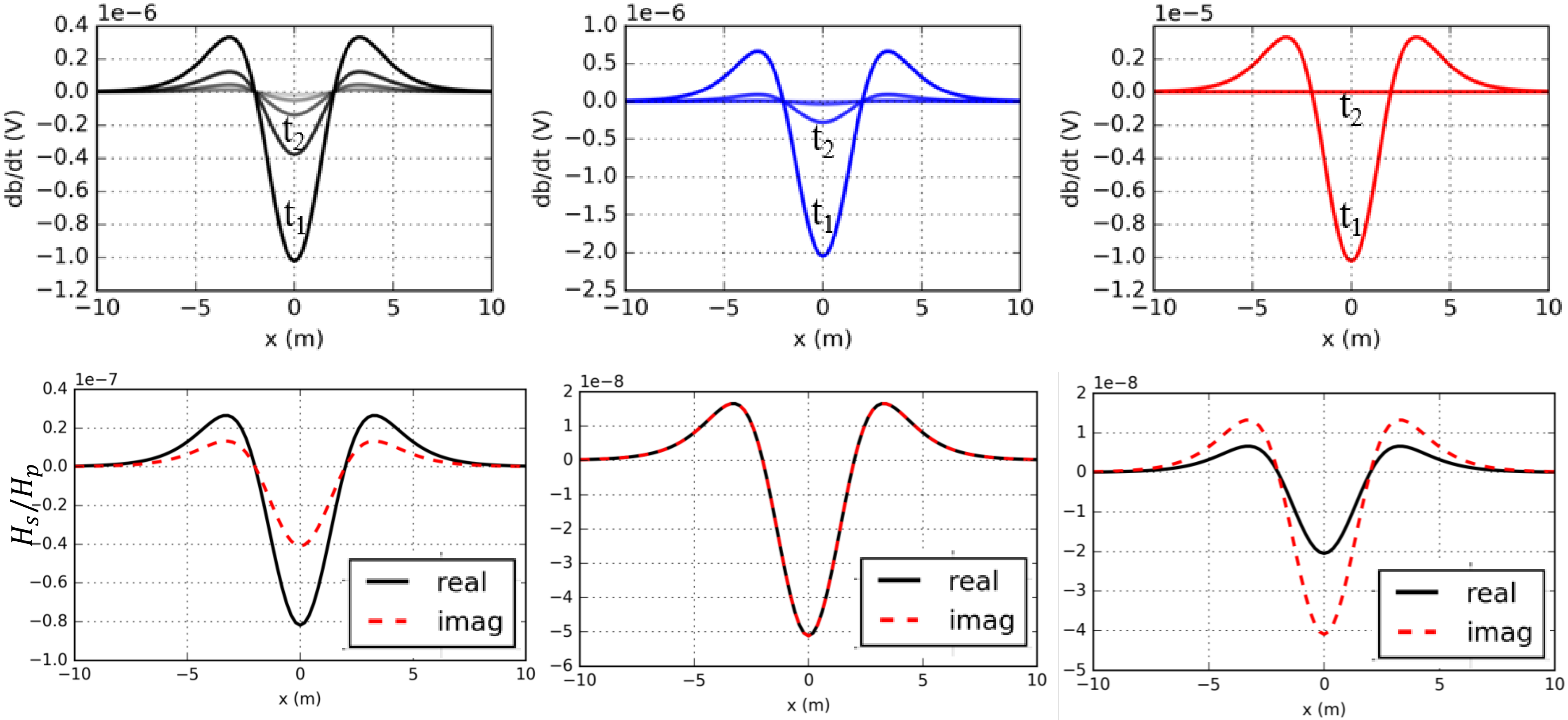


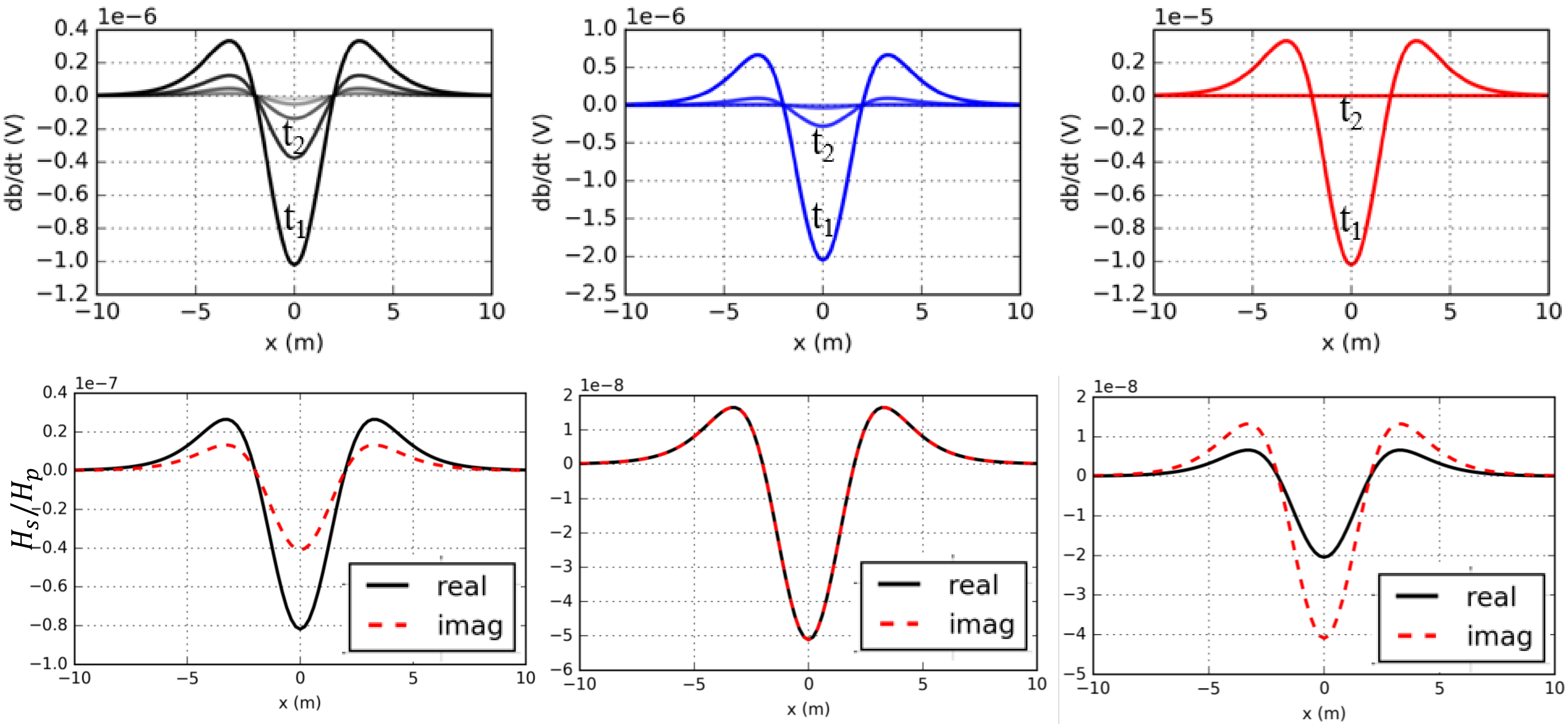
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

A summary



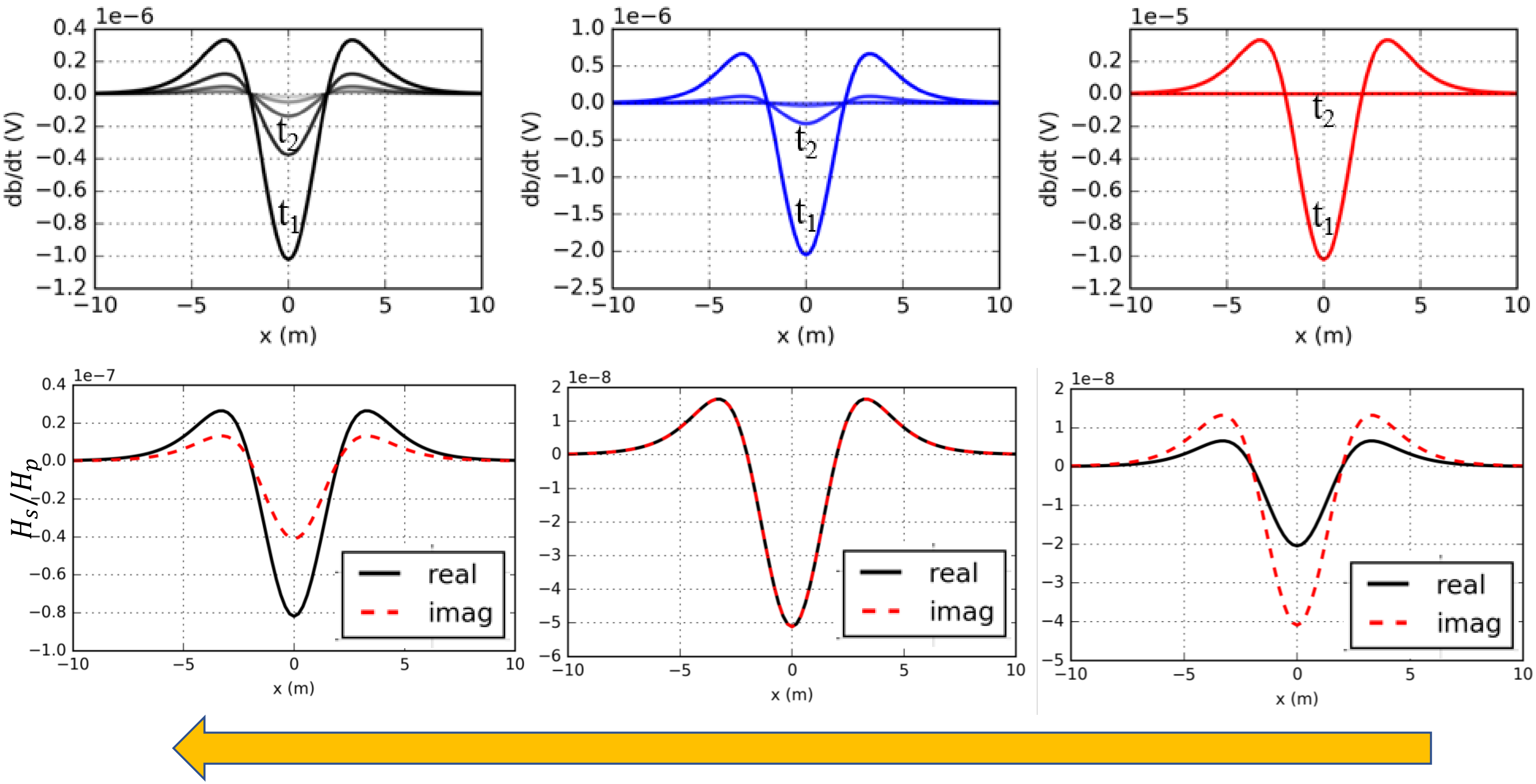
Much of what we see (e.g., the shape of the curve, the zero crossings) is from survey geometry (i.e., coupling, or the relative position of target w.r.t Tx & Rx).

A summary



But what we are really interested in is conductivity. In time domain, the decay rate tells you how conductive a target is. In frequency domain, the relative amplitudes of the real and imaginary curves tell about conductivity.

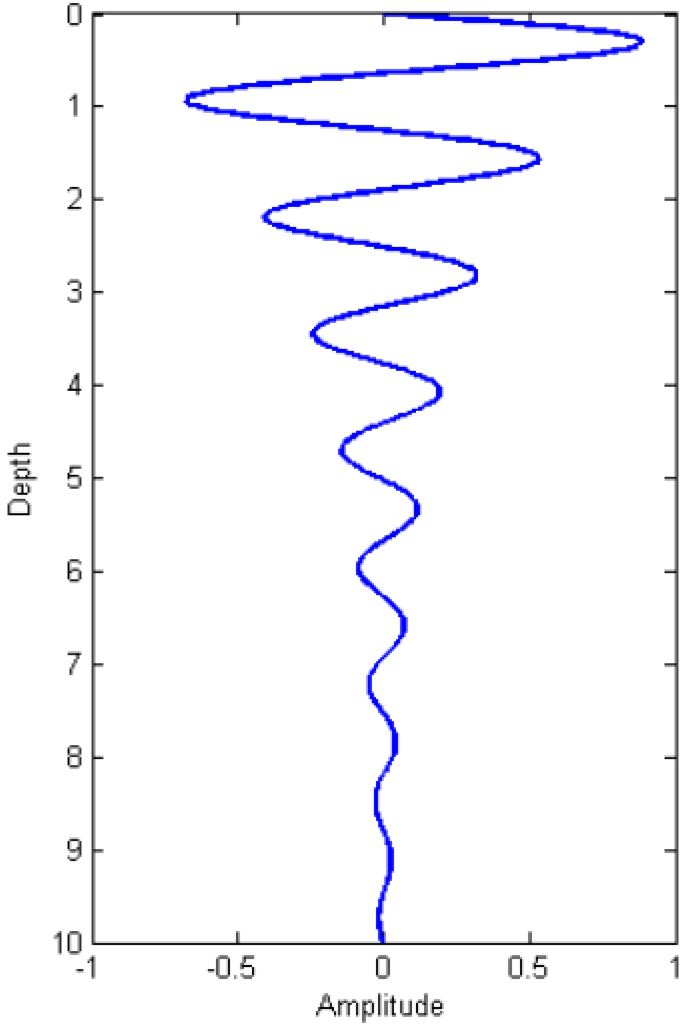
A summary



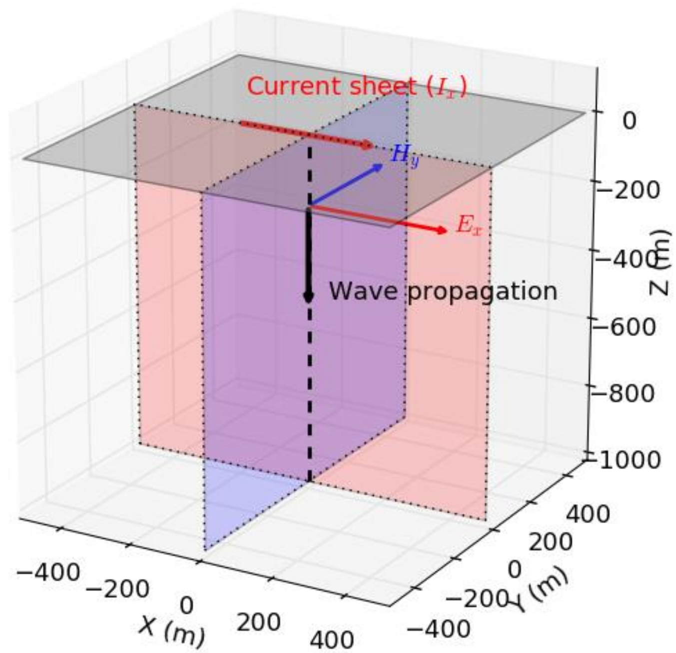
Strong conductor

Weak conductor

Plane waves in a homogeneous media: frequency domain



Plane wave solution



$$\mathbf{H} = \mathbf{H_0} \underbrace{e^{-\alpha z}}_{\text{attenuation}} e^{-i\underbrace{(\beta z - \omega t)}_{\text{phase}}}$$

Agenda

- DC resistivity
- RL circuit
- Plane waves
- Inductive source EM
- Grounded source EM

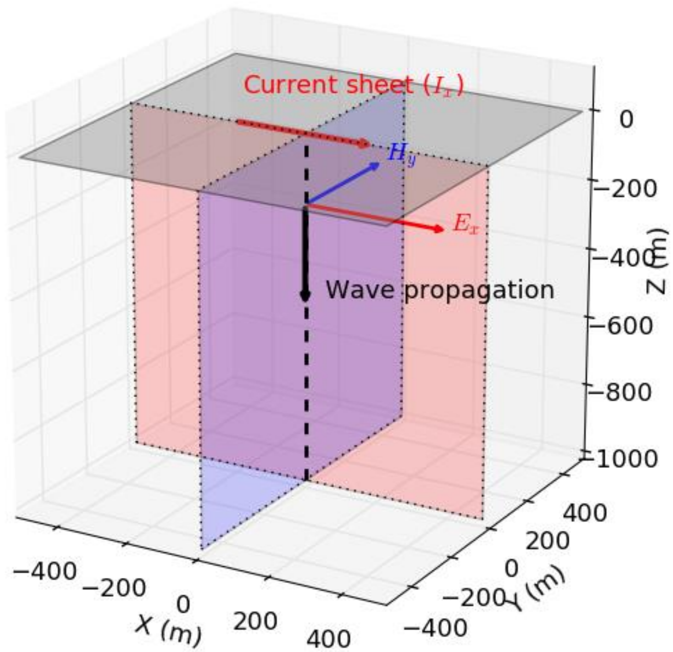
Plane waves

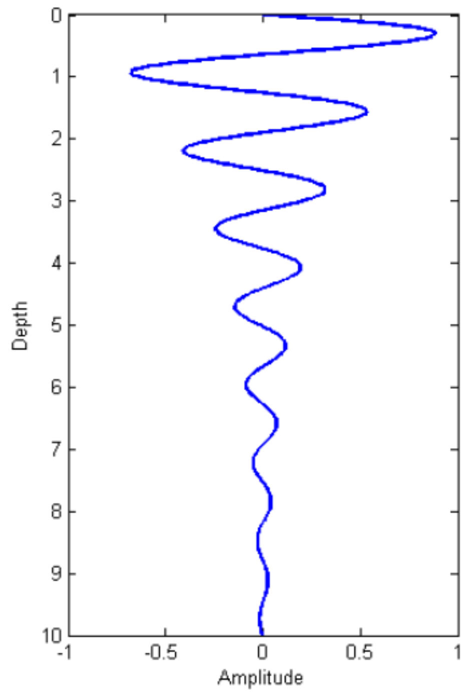
- Understanding skin depth and how to calculate it (for frequency domain EM)

- Understanding diffusion distance and how to calculate it (for time domain EM)

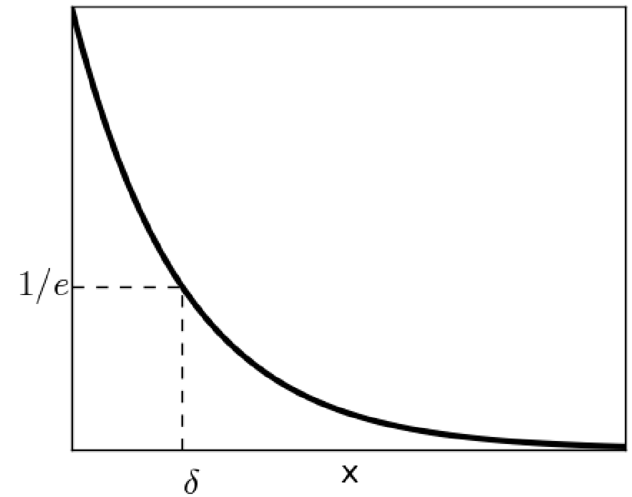
Skin depth

Plane wave solution





δ : skin depth



$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = 503\sqrt{\frac{1}{\sigma f}}$$

$$\mathbf{H} = \mathbf{H_0} \underbrace{e^{-\alpha z}}_{\text{attenuation}} \underbrace{e^{-i(\beta z - \omega t)}}_{\text{phase}}$$

Plane waves in a homogeneous media: time domain

$$\nabla^2 \mathbf{h} - \mu\epsilon \frac{\partial^2 \mathbf{h}}{\partial t^2} - \mu\sigma \frac{\partial \mathbf{h}}{\partial t} = 0$$

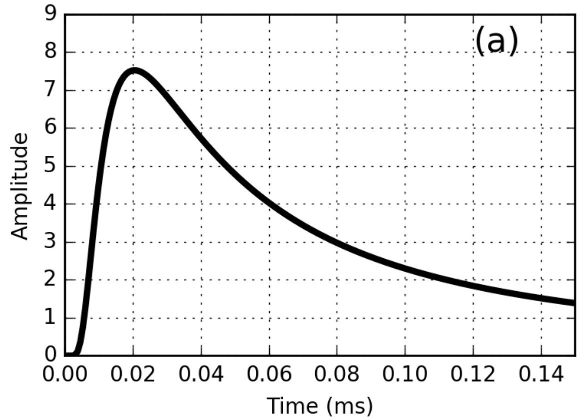
$$\mathbf{h}(t=0) = \mathbf{h}_0 \delta(t)$$

Solution for quasi-static

$$\mathbf{h}(t) = -\frac{(\mu\sigma)^{1/2} z}{2\pi^{1/2} t^{3/2}} e^{-\mu\sigma z^2/(4t)}$$

$$z\text{: depth (m)}$$

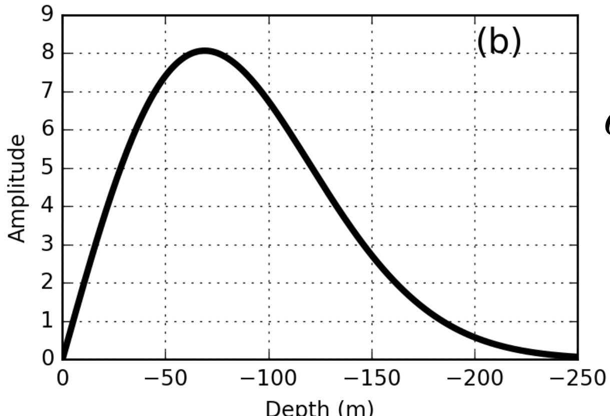
Peak time:



$$t_{max} = \frac{\mu\sigma z^2}{6}$$

Electric field as a function of time at 100 m from a 1D impulse in the field in a 0.01 S/m whole space

Diffusion distance



$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

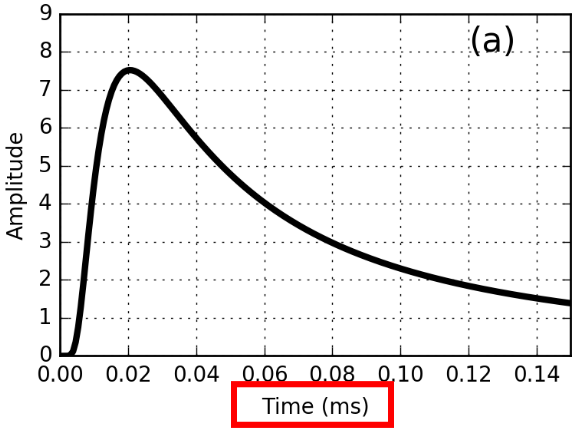
$$\approx 1260\sqrt{\frac{t}{\sigma}}$$

Electric field at t = 0.03 ms as a function of distance

Plane waves in a homogeneous media: time domain

At any given depth z, when does the maximum field (e.g., magnetic field) occur?

Peak time:

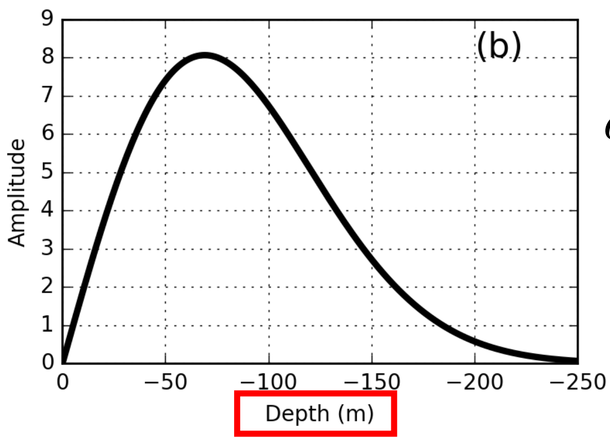


$$t_{max} = \frac{\mu \sigma z^2}{6}$$

At any given time t , where does the maximum field (e.g., magnetic field) occur?

Also called peak distance

Diffusion distance



$$d = \sqrt{\frac{2t}{\mu \sigma}}$$

$$\approx 1260\sqrt{\frac{t}{\sigma}}$$

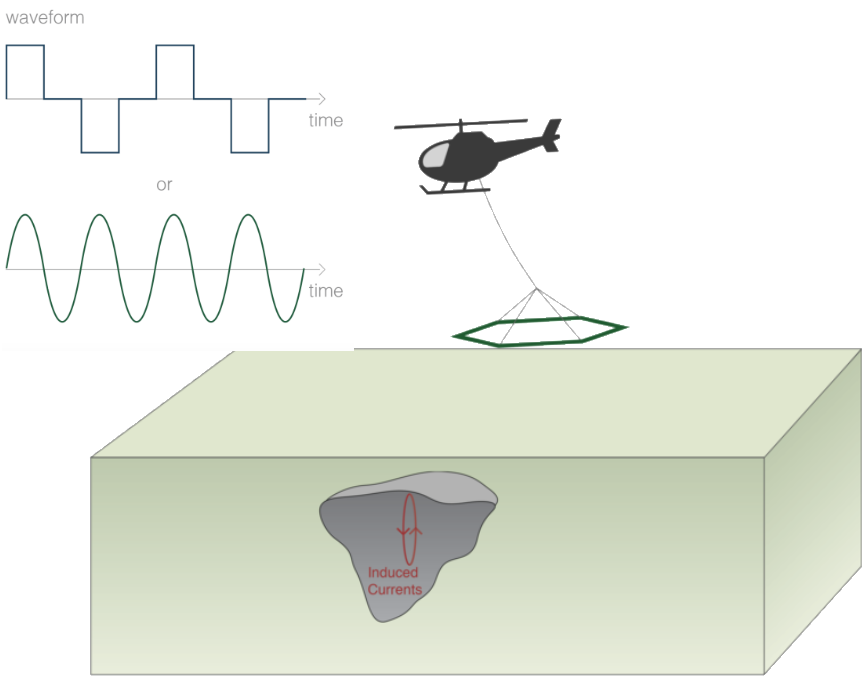
Agenda

- DC resistivity
- RL circuit
- Plane waves
- Inductive source EM
- Grounded source EM

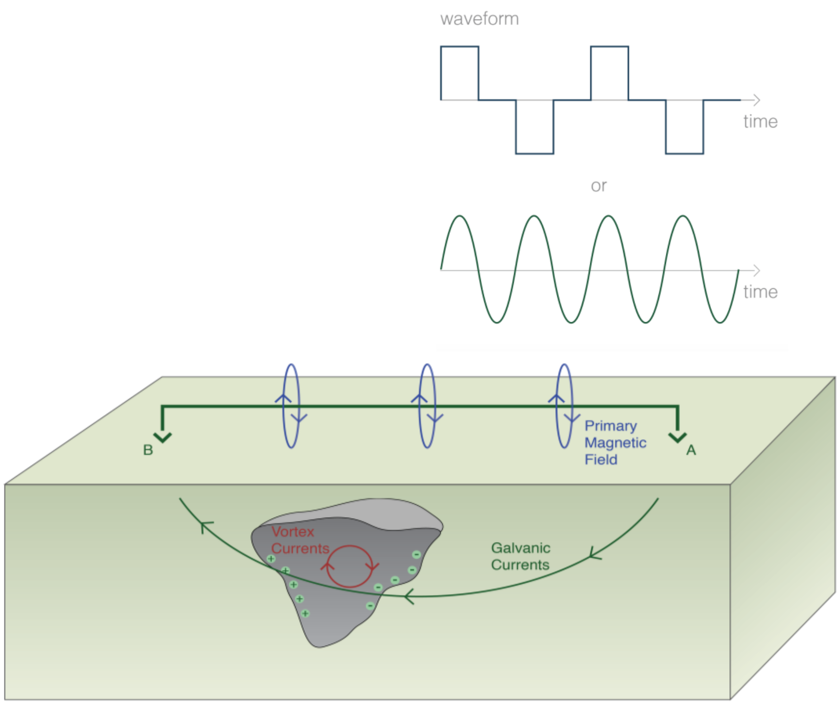
Inductive source EM

- What is inductive source?
- Time-domain EM
  - How does current propagate in the Earth medium?
  - How to interpret db/dt curves?
- Frequency-domain EM
  - Interpret the measured (real and imaginary) data
- What is the limitation of inductive source EM?
- Understanding the shielding problem

Inductive source vs Grounded sources



Inductive sources

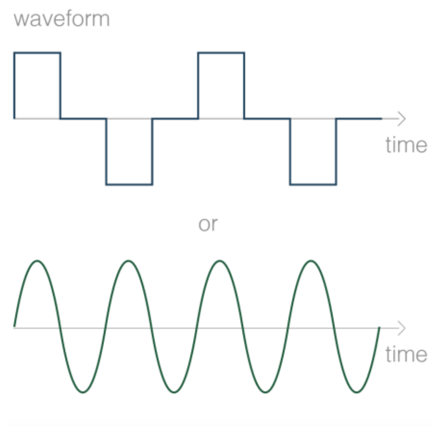


Grounded sources

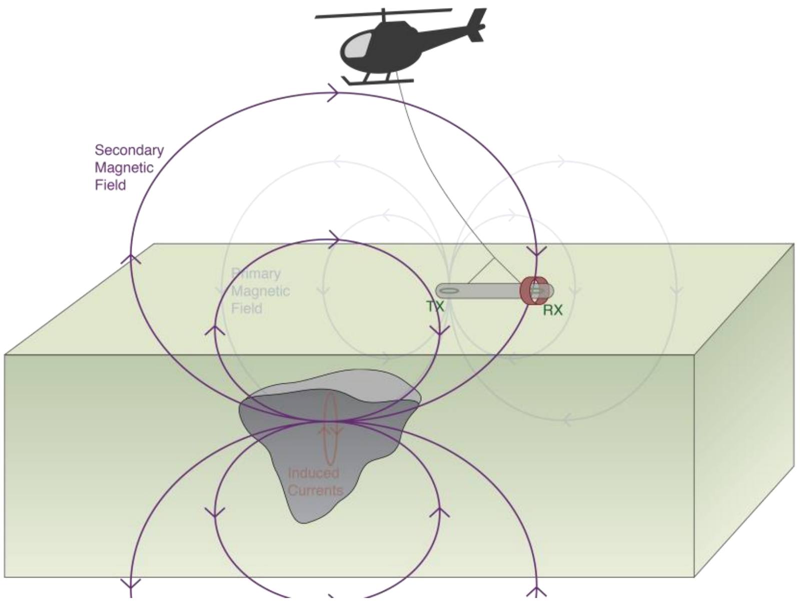
No direct contact between transmitter and the Earth's subsurface

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Basic Experiment



- **Transmitter:**
  - Produces a primary magnetic field
- **Exciting the target:**
  - Time varying magnetic fields generate electric fields everywhere
  - Producing currents in conductors
- **Receiver:**
  - Induced currents produce secondary magnetic fields

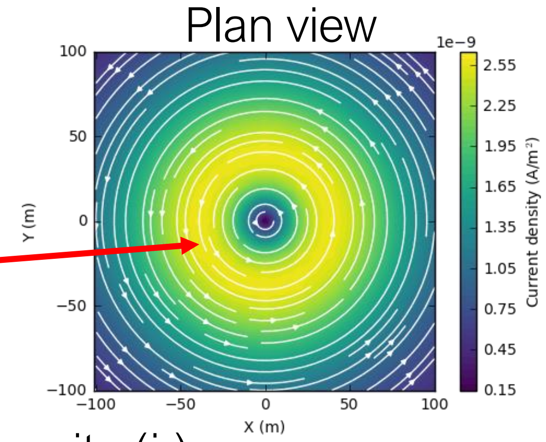


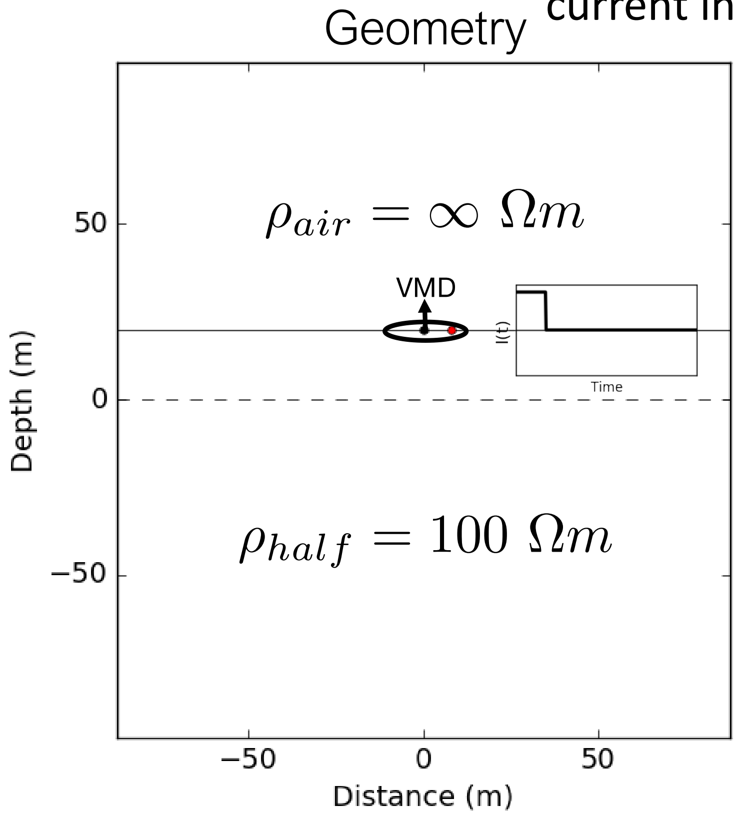
Time-domain EM: inductive source

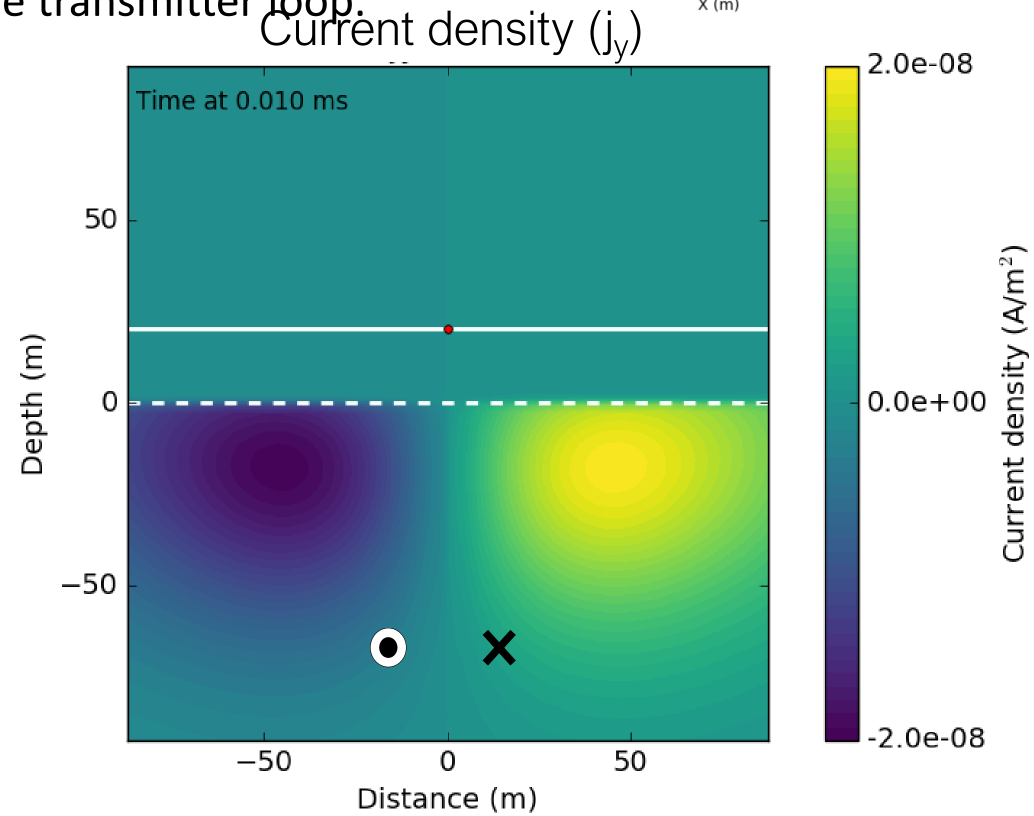
Current Density

- Time: 0.01ms

The nature wants to preserve the magnetic field produced by the current in the transmitter loop so desperately that it creates an induced current that looks like the current in the transmitter loop.







Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

$$d = 1260\sqrt{t\rho}$$

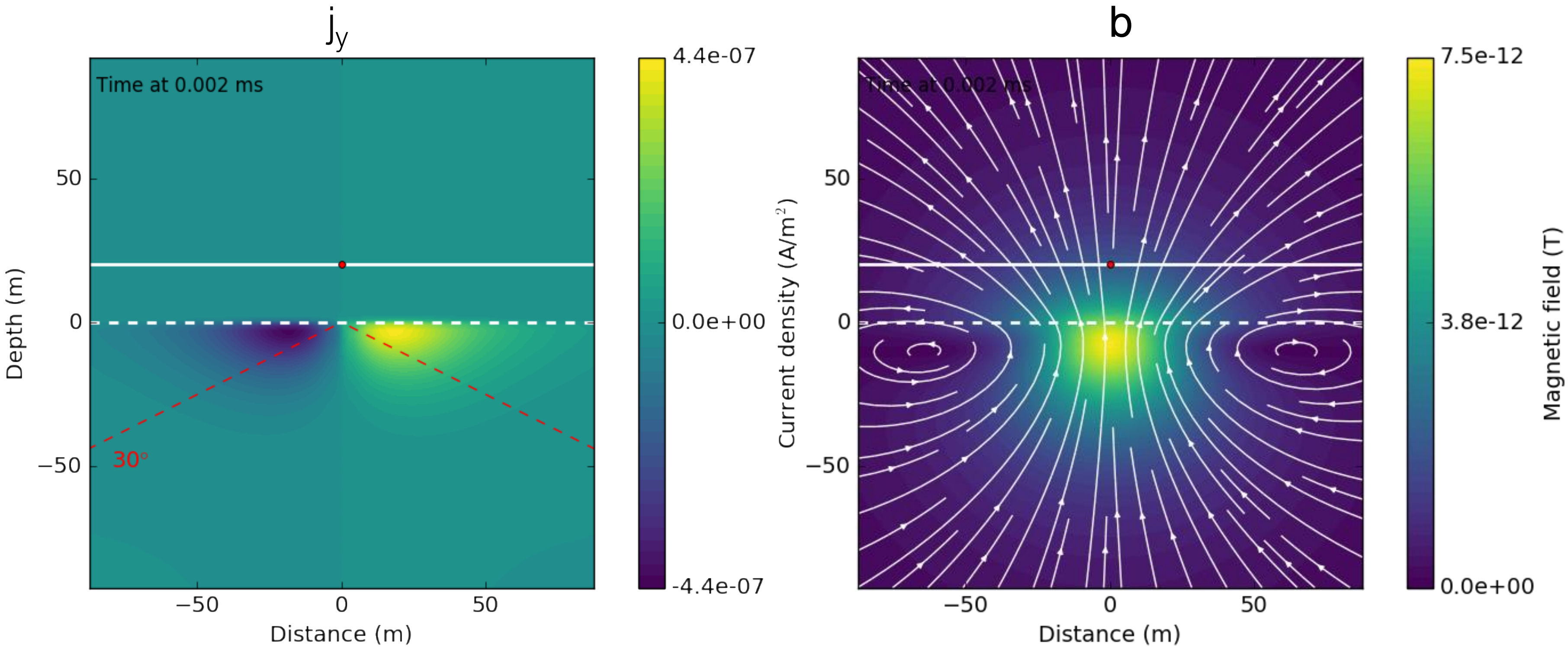


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

$$d = 1260\sqrt{t\rho}$$

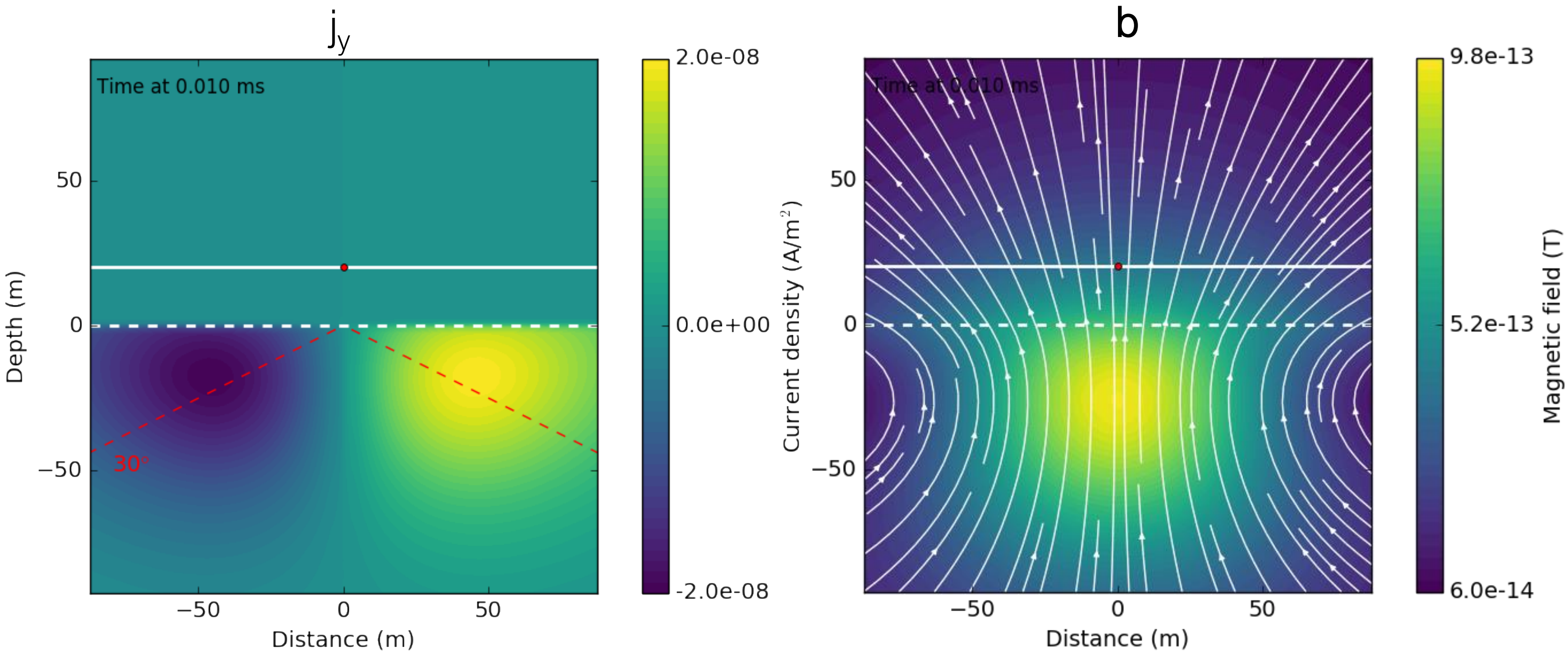


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

$$d = 1260\sqrt{t\rho}$$

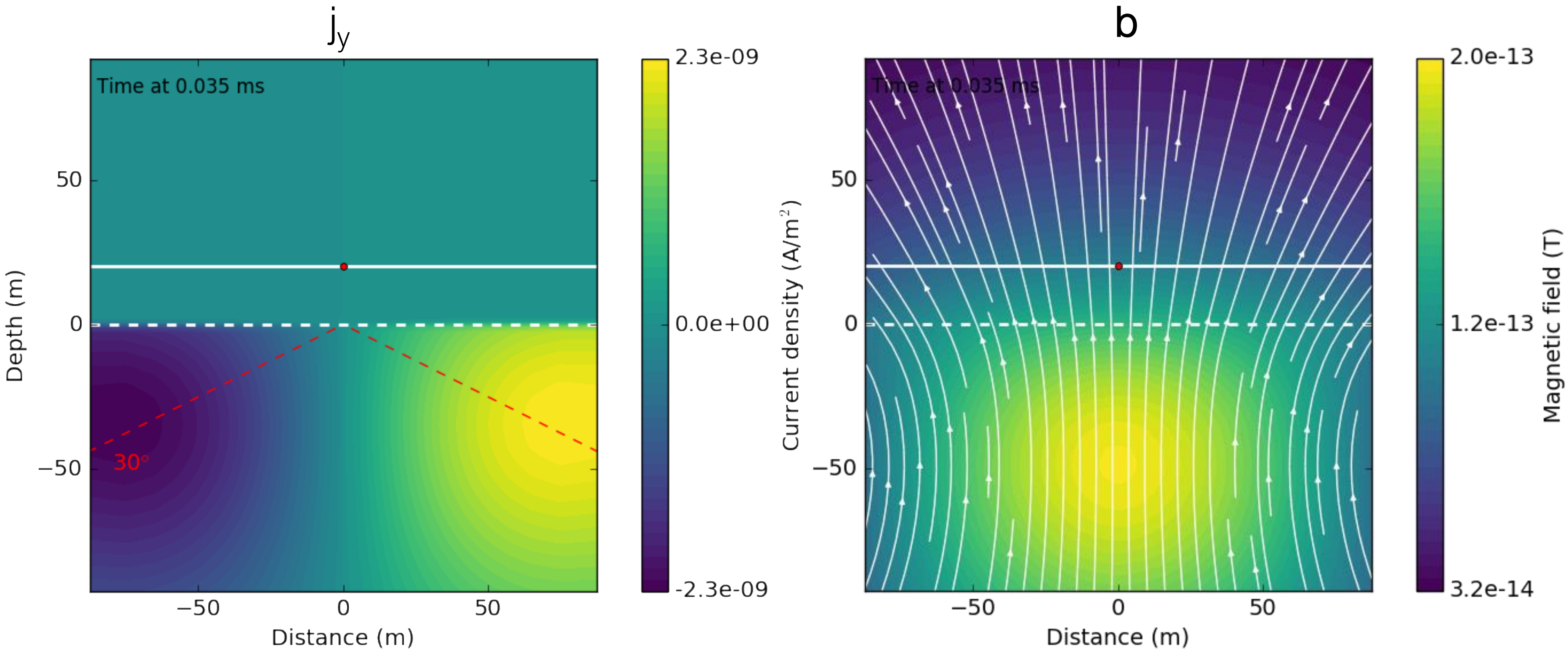


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Propagation through time

- Time: 0.110ms
- diffusion distance = 132 m

$$d = 1260\sqrt{t\rho}$$

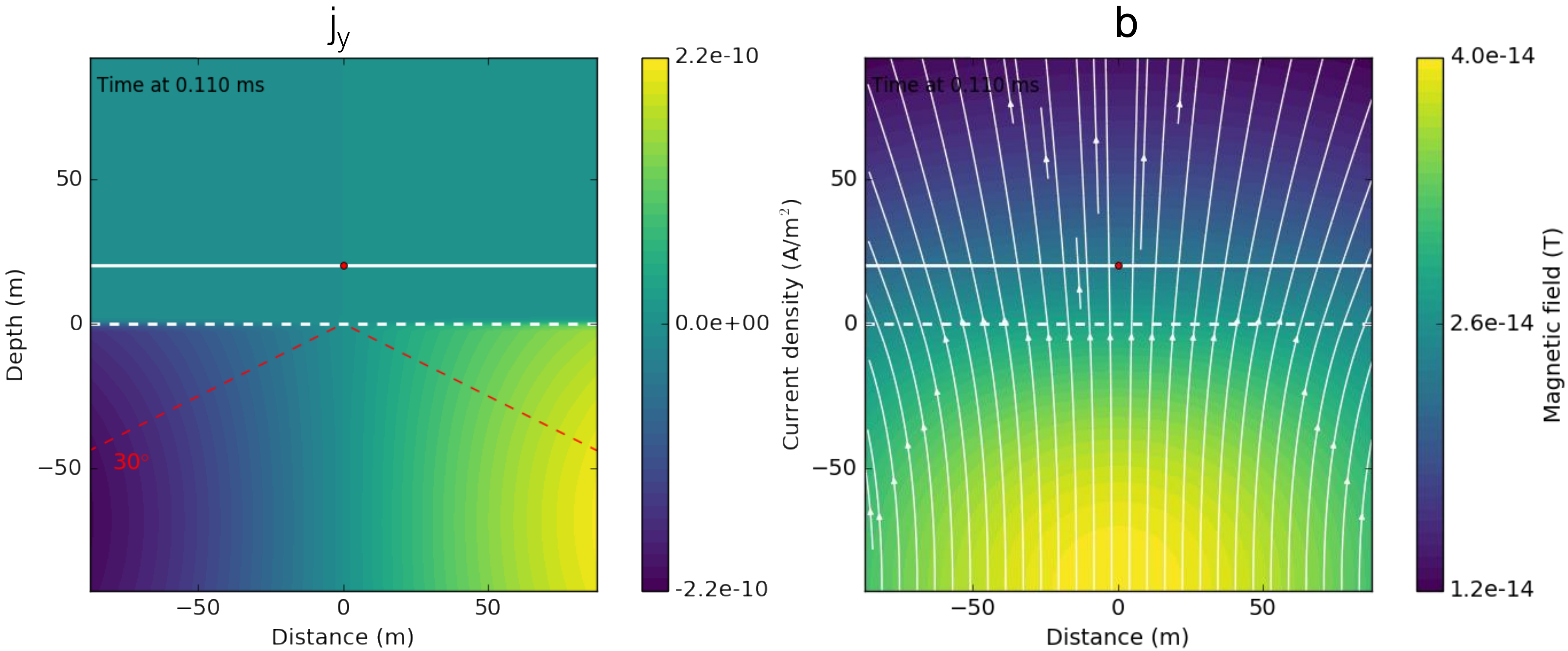
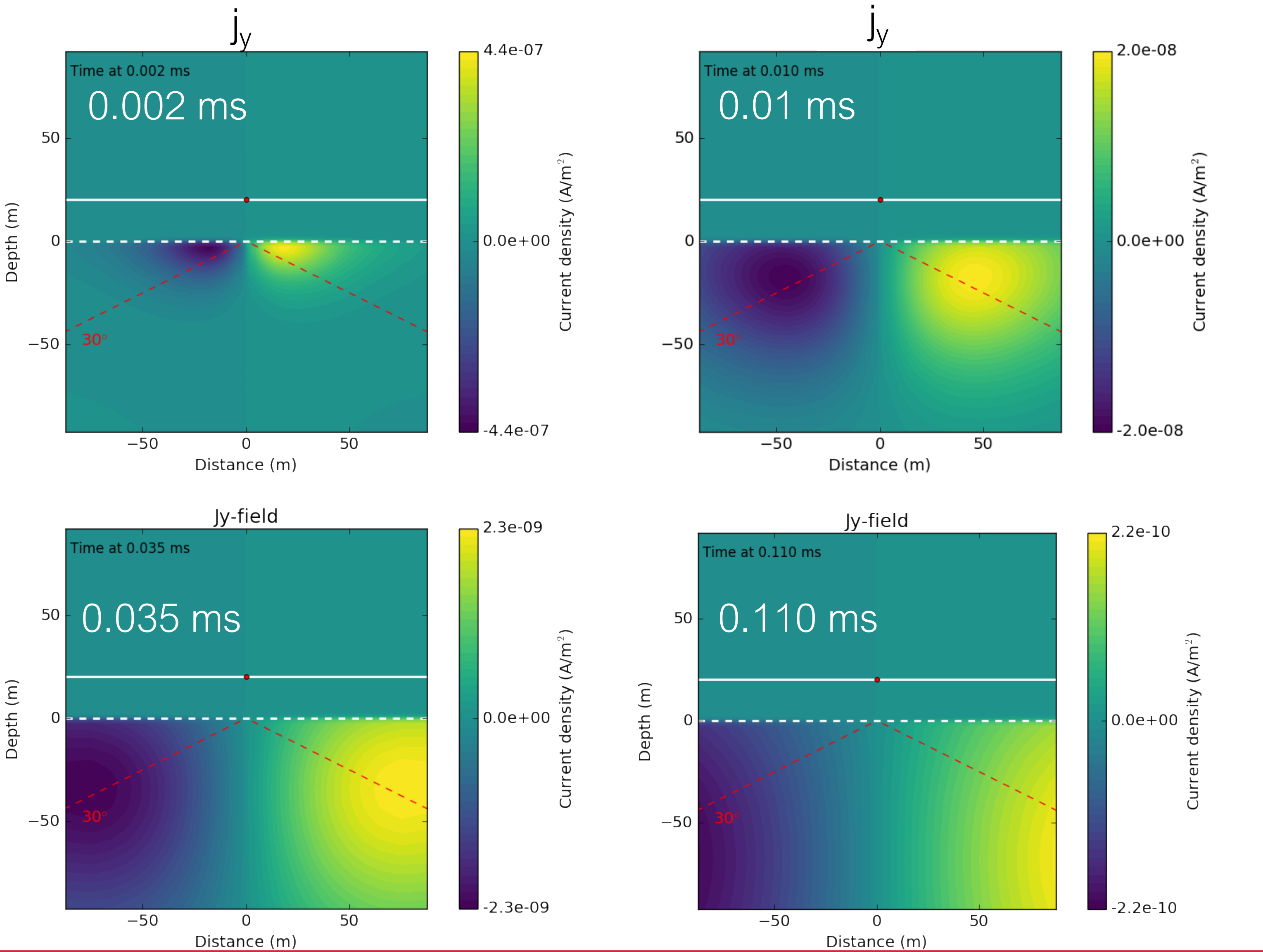
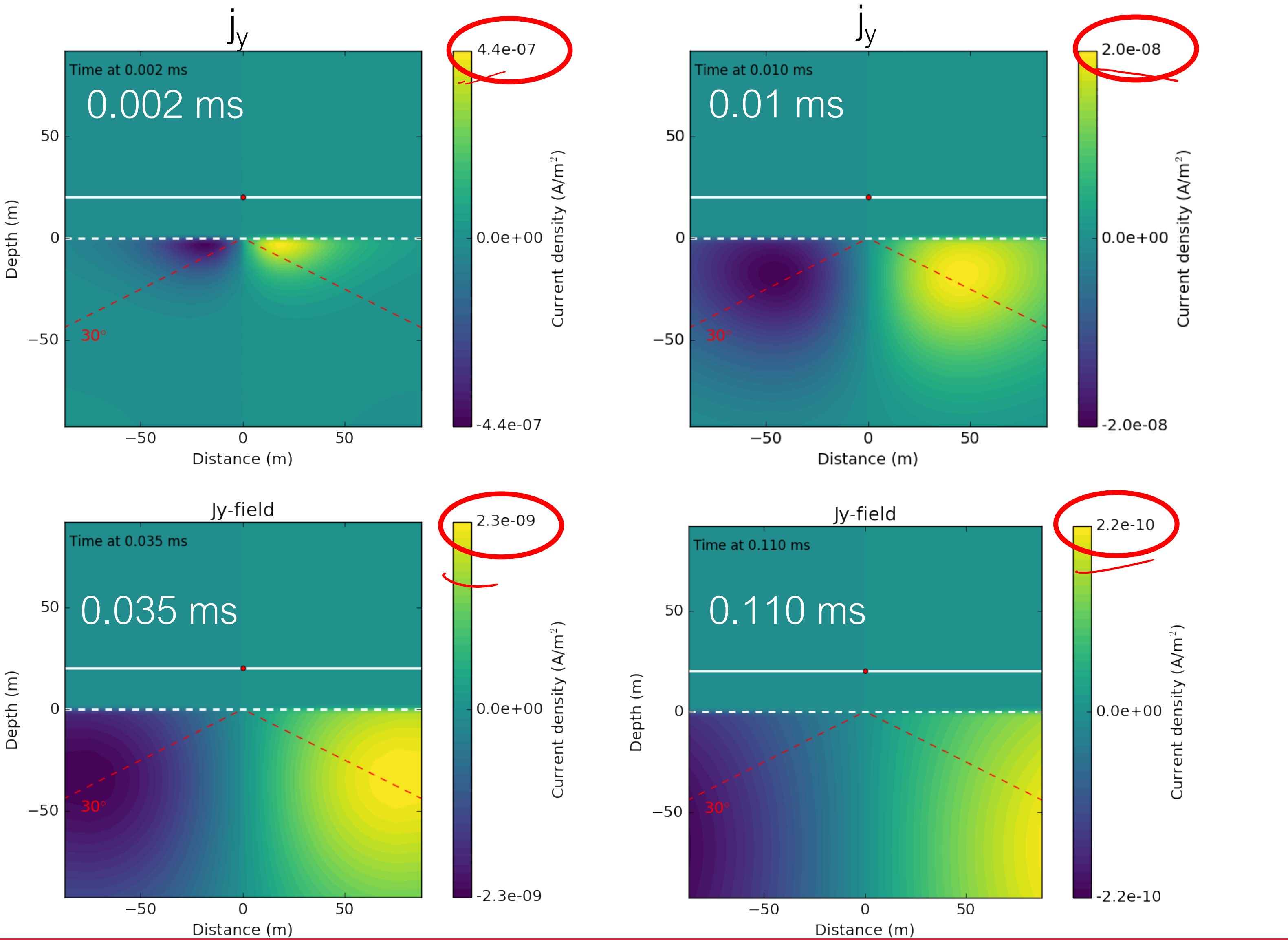


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Summary: propagation through time



Summary: propagation of current through time



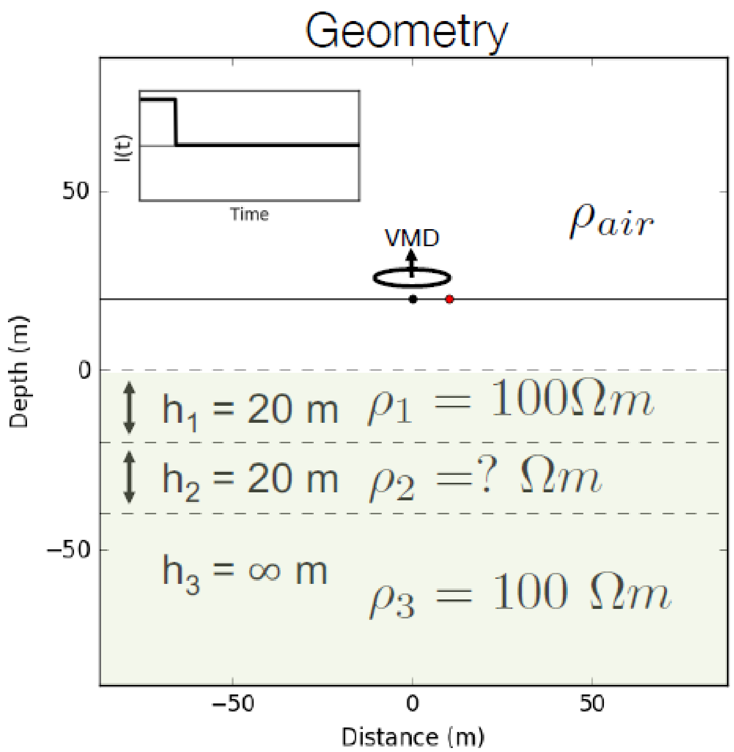
Observation

- The current propagates downward and outward.
- The current becomes smaller and smaller when propagating.
- The current becomes more and more diffused (i.e., less and less focused)

diffusion

Layered earth model

- 3 layers + air,
- ρ_2 varies

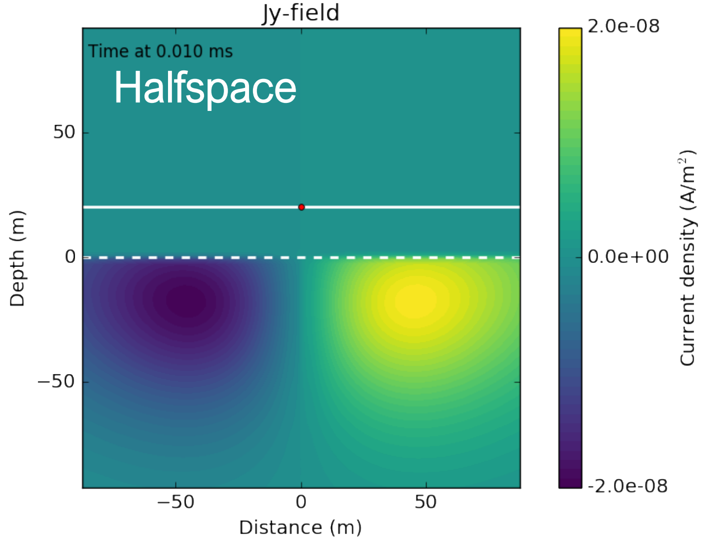


- Four different cases:
  - Halfspace
    $\rho_2 = 100\ \Omega\mathrm{m}$
  - Resistive
    $\rho_2 = 1000\ \Omega\mathrm{m}$
  - Conductive
    $\rho_2 = 10\ \Omega\mathrm{m}$
  - Very conductive
    $\rho_2 = 1\ \Omega\mathrm{m}$
- Fields
  - j_y off-time
  - b off-time

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

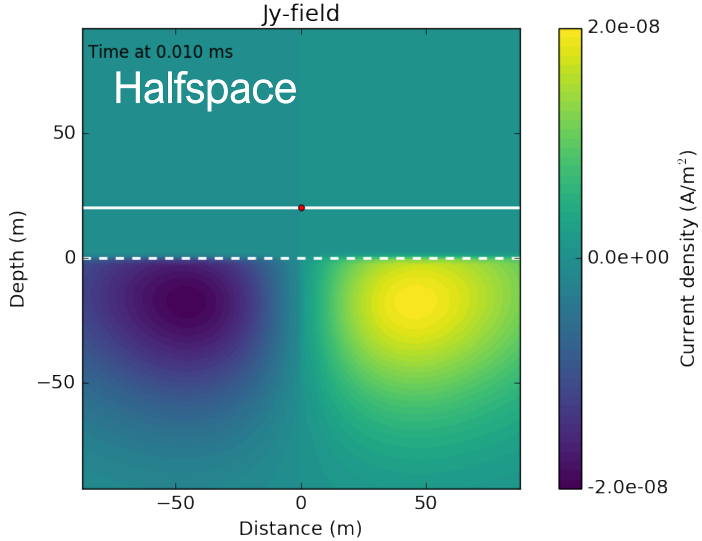
Layered earth currents (j_y)

ρ_2 = 100 Ωm



Layered earth currents (j_y)

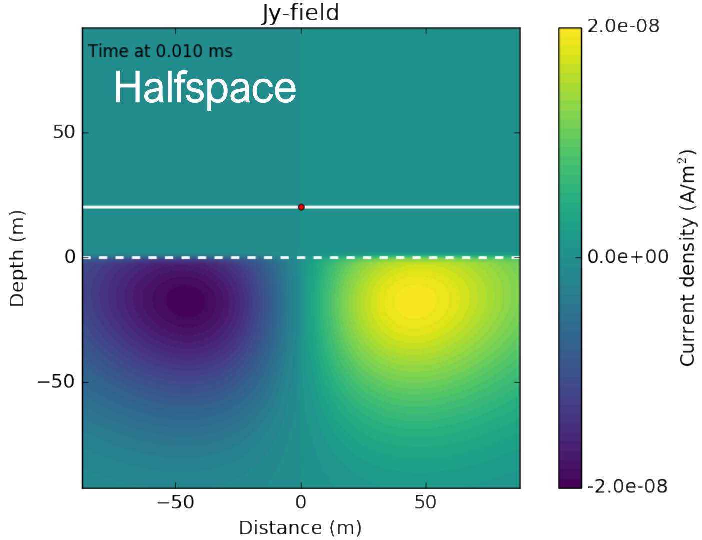
ρ_2 = 100 Ωm



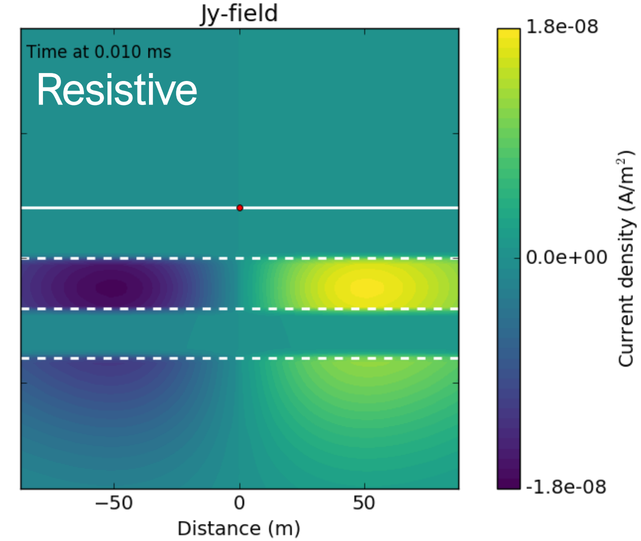
ρ_2 = 1000 Ωm

Layered earth currents (j_y)

ρ_2 = 100 Ωm

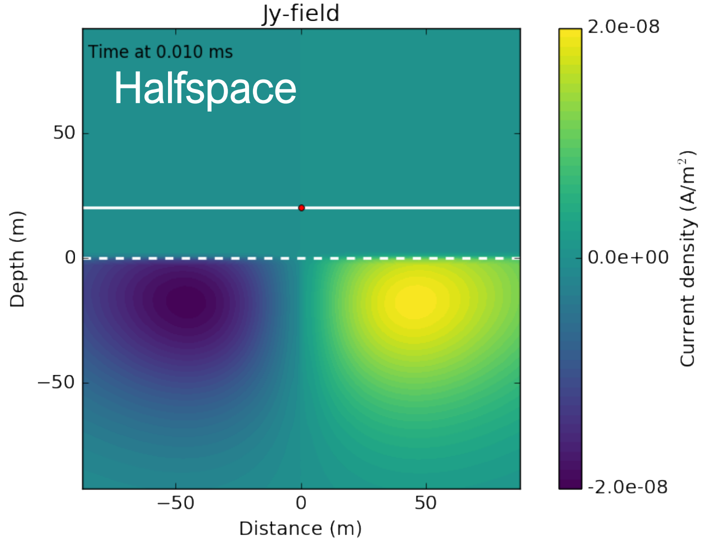


ρ_2 = 1000 Ωm

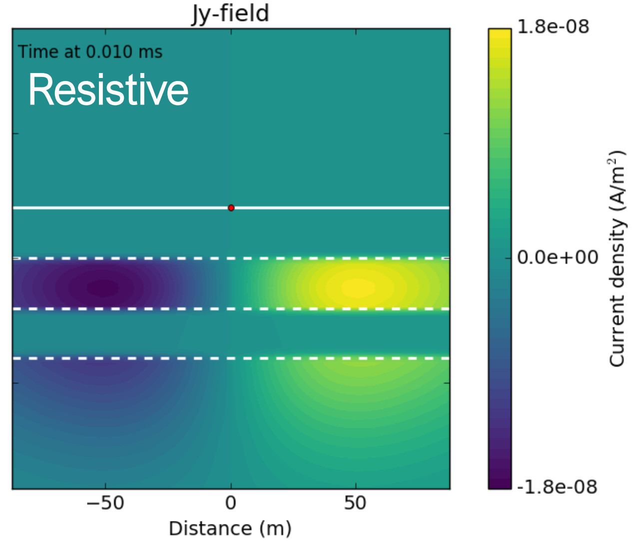


Layered earth currents (j_y)

ρ_2 = 100 Ωm



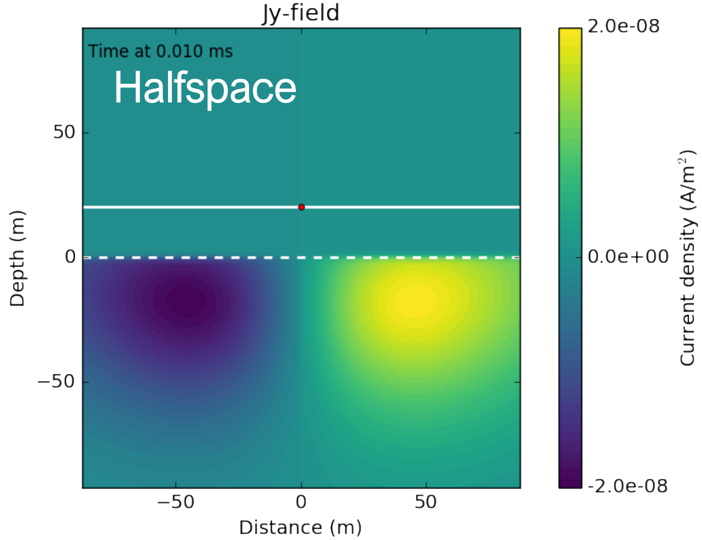
ρ_2 = 1000 Ωm



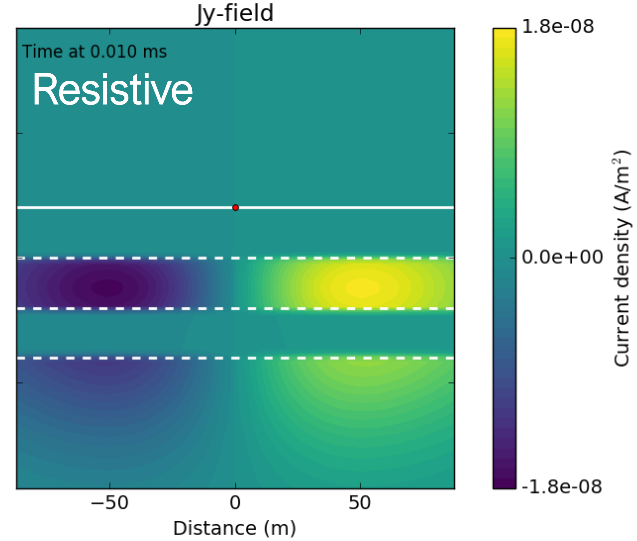
ρ_2 = 10 Ωm

Layered earth currents (j_y)

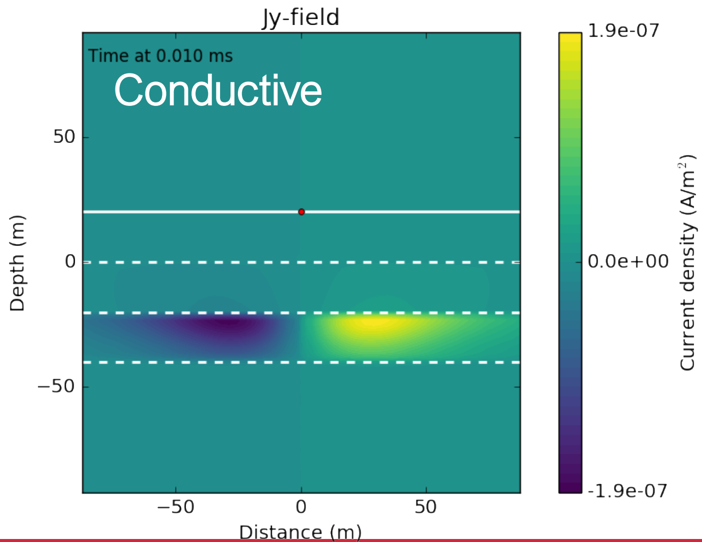
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm

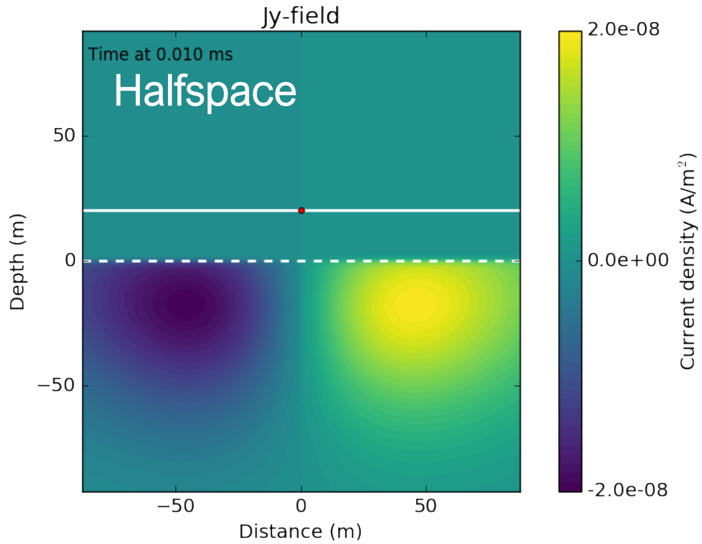


ρ_2 = 10 Ωm

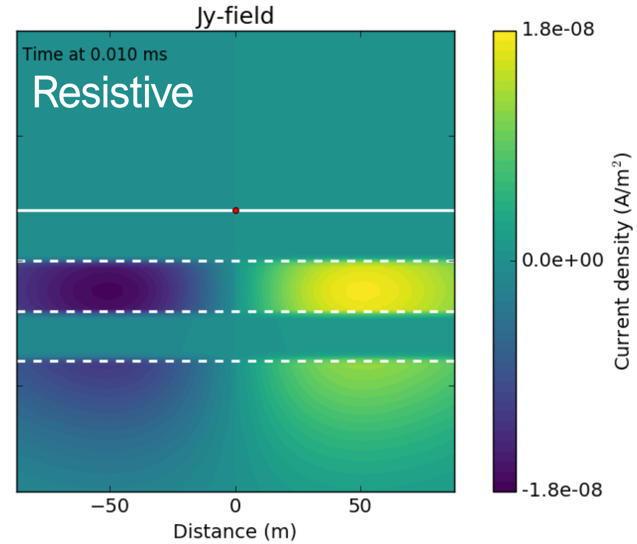


Layered earth currents (j_y)

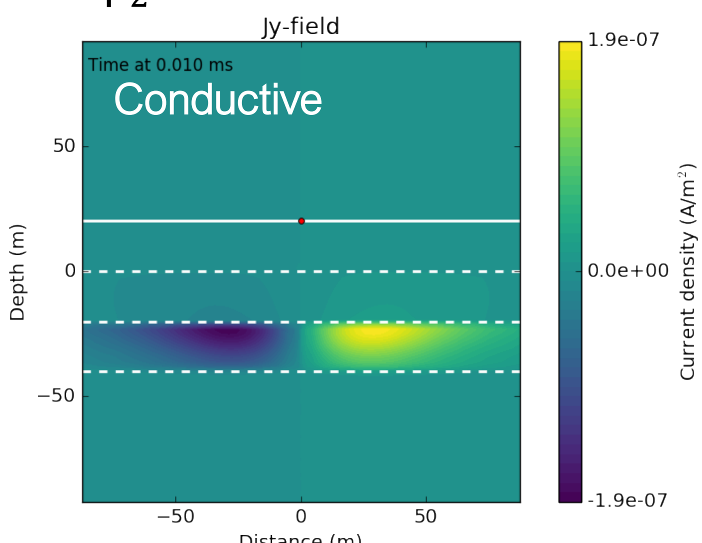
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm

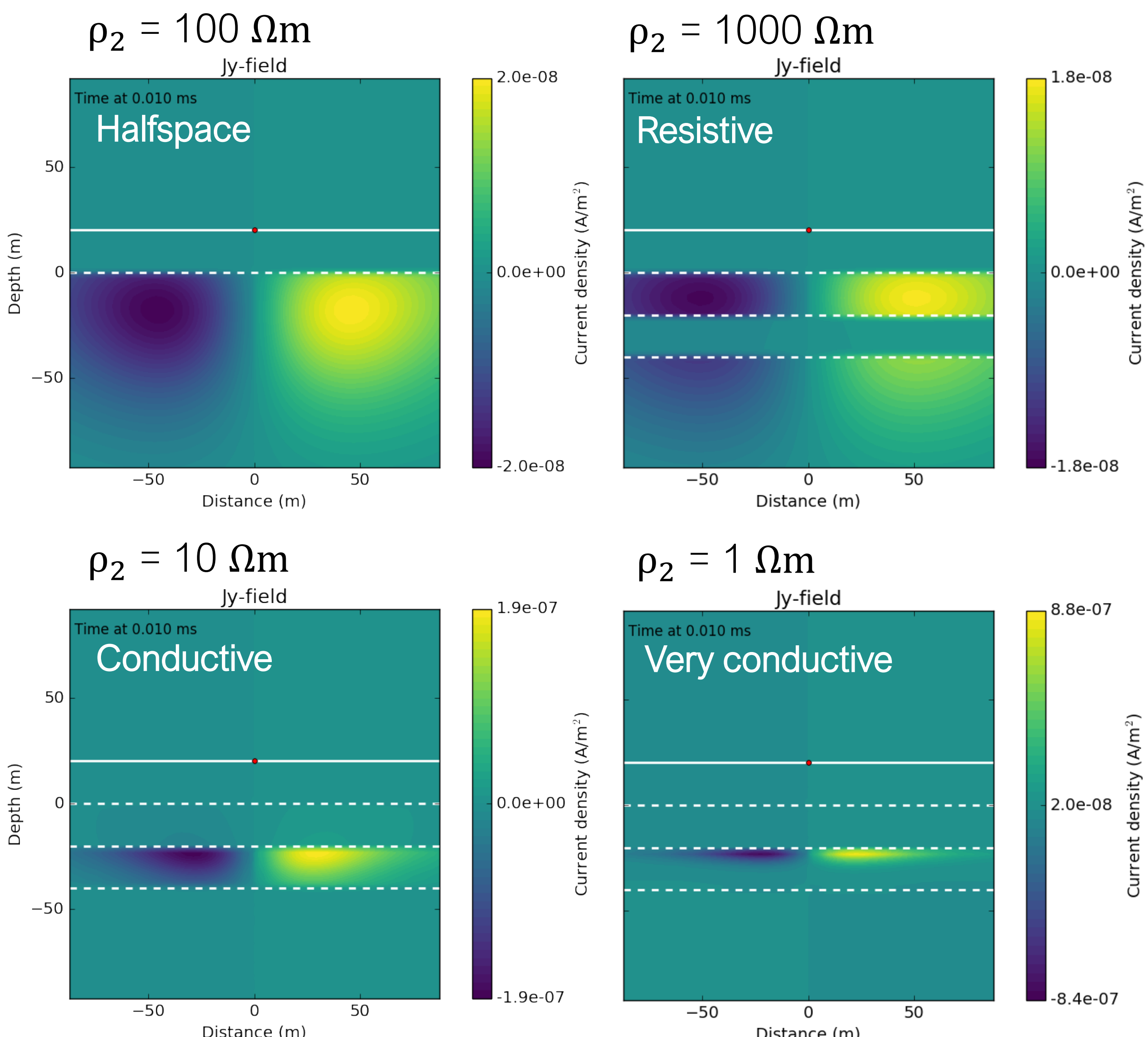


ρ_2 = 10 Ωm



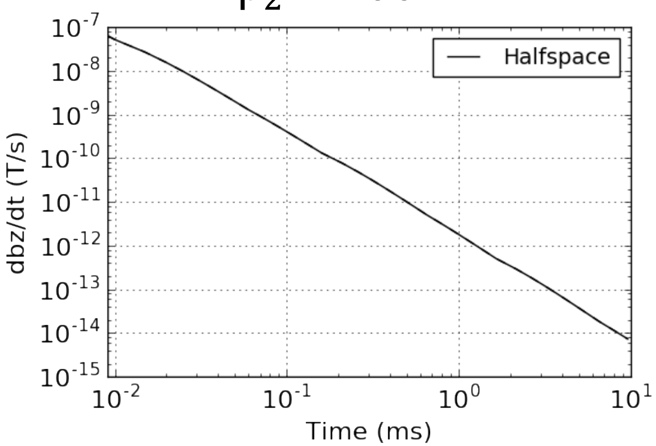
ρ_2 = 1 Ωm

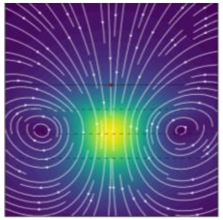
Layered earth currents (j_y)



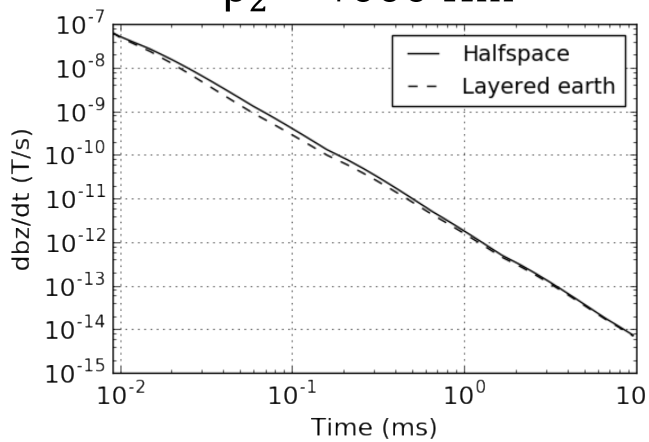
db_z/dt sounding curves

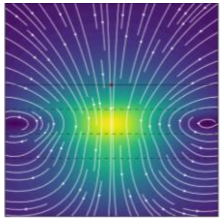
ρ_2 = 100 Ωm



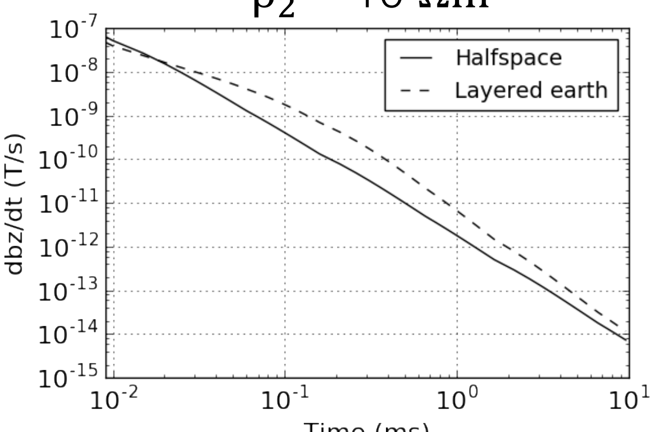


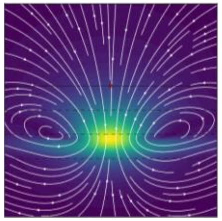
ρ_2 = 1000 Ωm



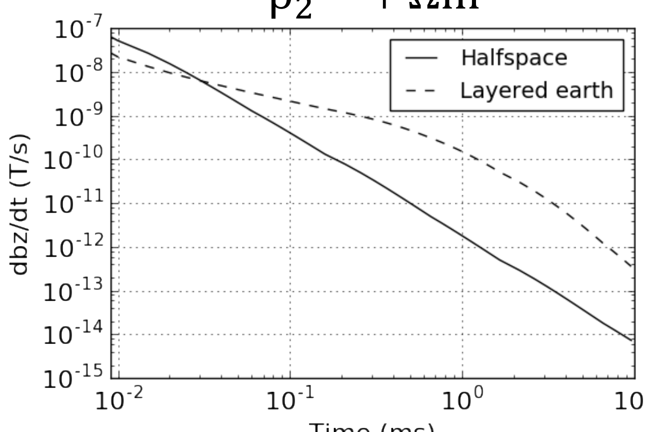


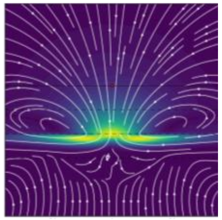
ρ_2 = 10 Ωm





ρ_2 = 1 Ωm





Observations

- EM signal decays slower in more conductive medium
- EM with inductive sources very sensitive to conductors (not so sensitive to resistors)

Frequency-domain EM: inductive source

Layered earth

- 3 layers + air,
- ρ_2 varies

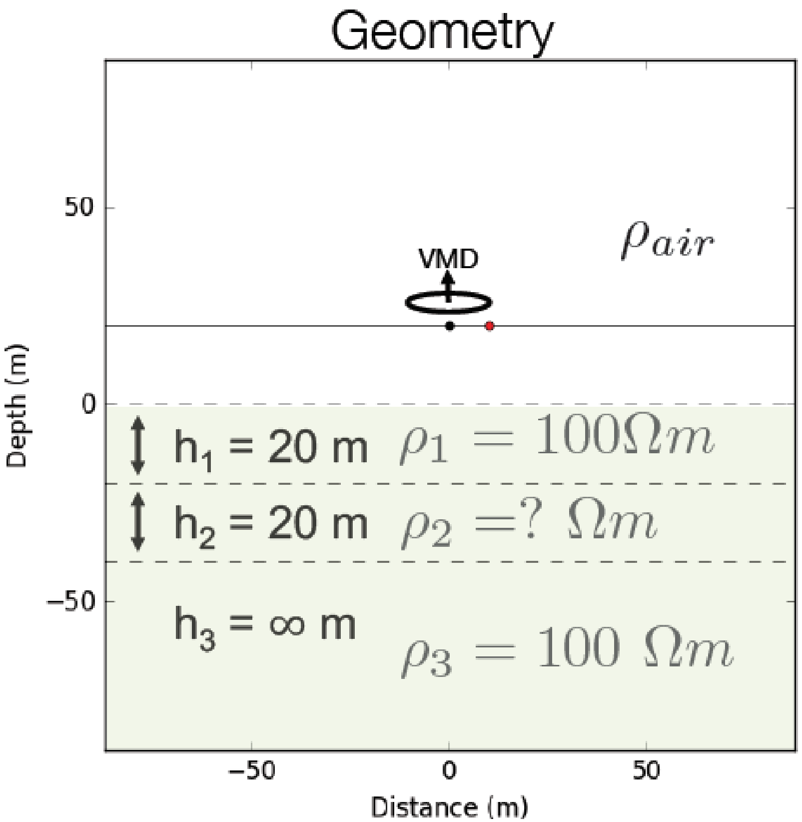
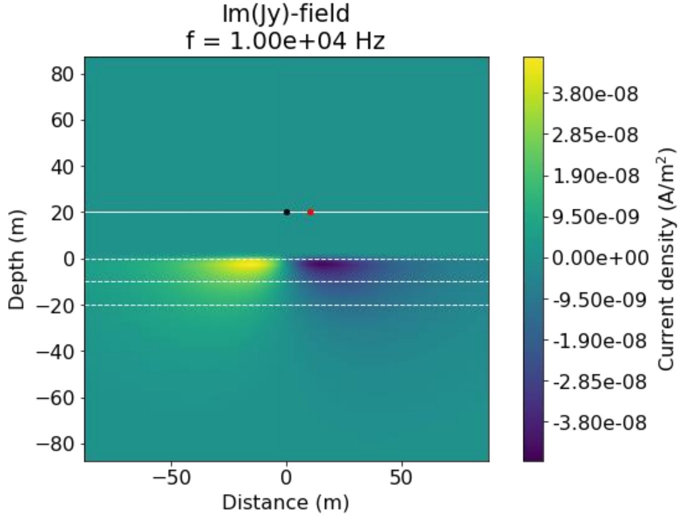


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

- Four different cases:
  - Halfspace
    $\rho_2 = 100\ \Omega\text{m}$
  - Resistive
    $\rho_2 = 1000\ \Omega\text{m}$
  - Conductive
    $\rho_2 = 10\ \Omega\text{m}$
  - Very conductive
    $\rho_2 = 1\ \Omega\text{m}$
- Fields
  - J_y imag
  - Secondary **B** imag

Current density (J_y imag)

ρ_2 = 100 Ωm



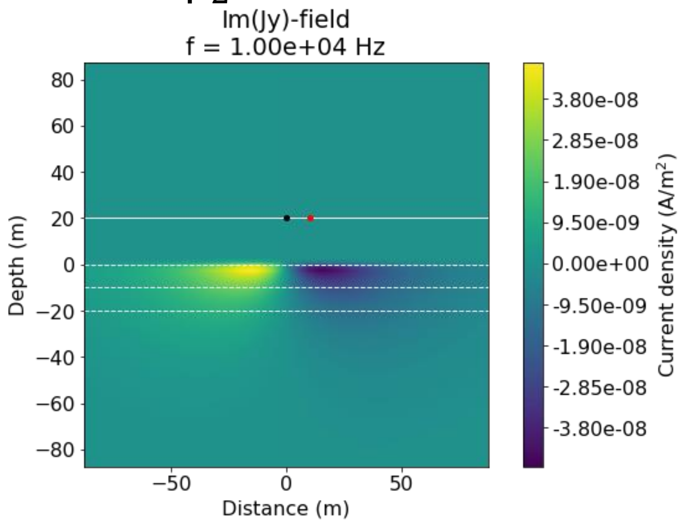
ρ_2 = 1000 Ωm

ρ_2 = 10 Ωm

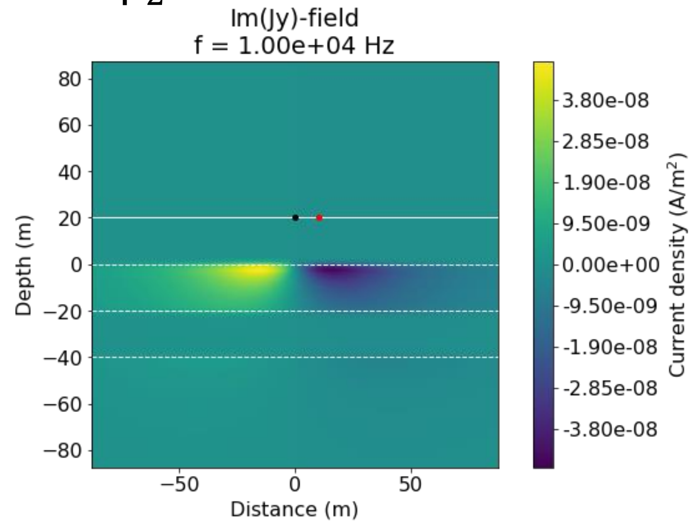
ρ_2 = 1 Ωm

Current density (J_y imag)

ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm

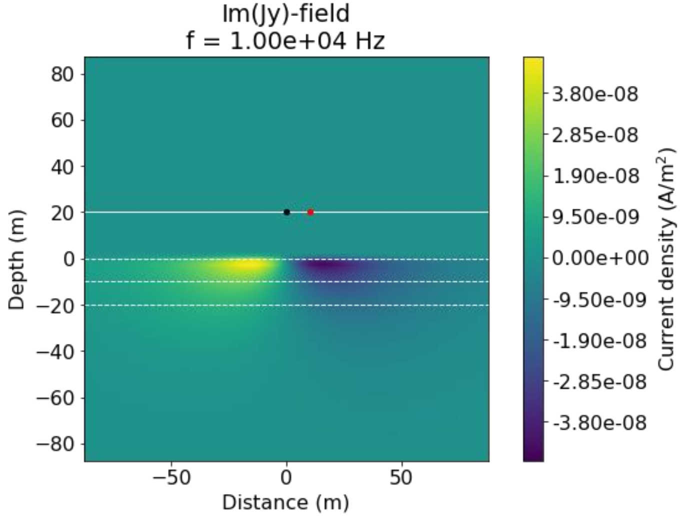


ρ_2 = 10 Ωm

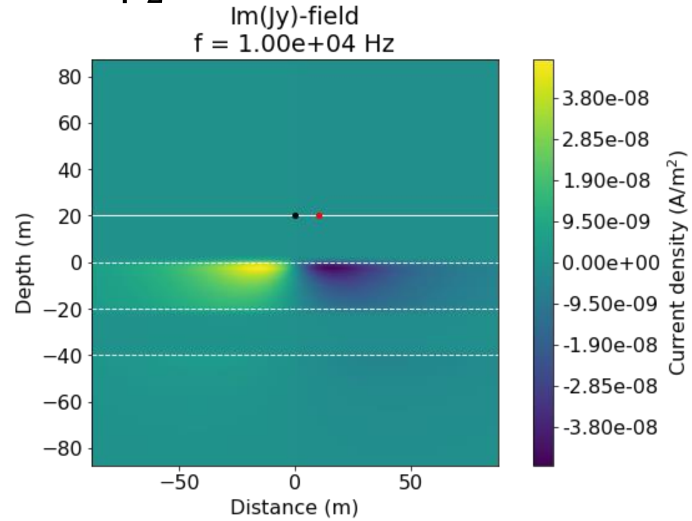
ρ_2 = 1 Ωm

Current density (J_y imag)

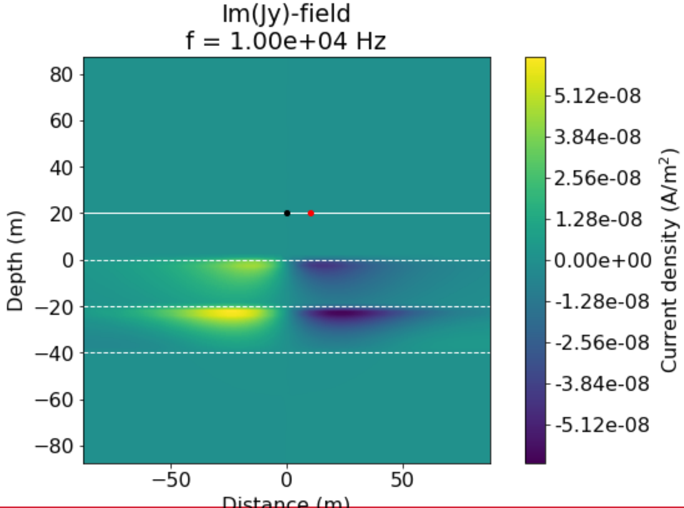
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm

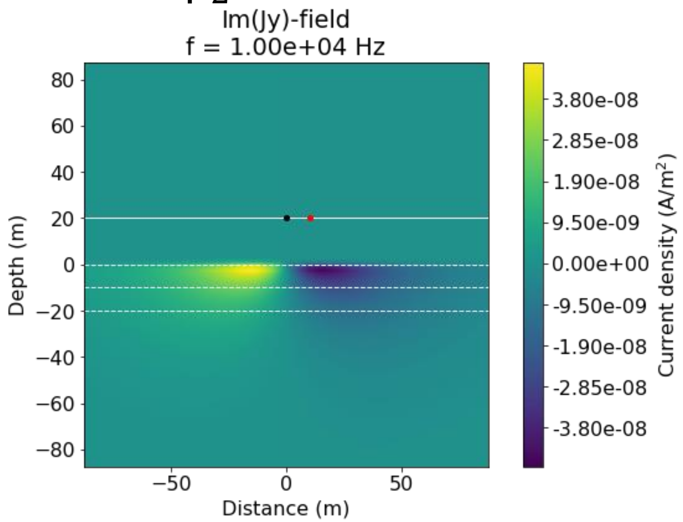


ρ_2 = 1 Ωm

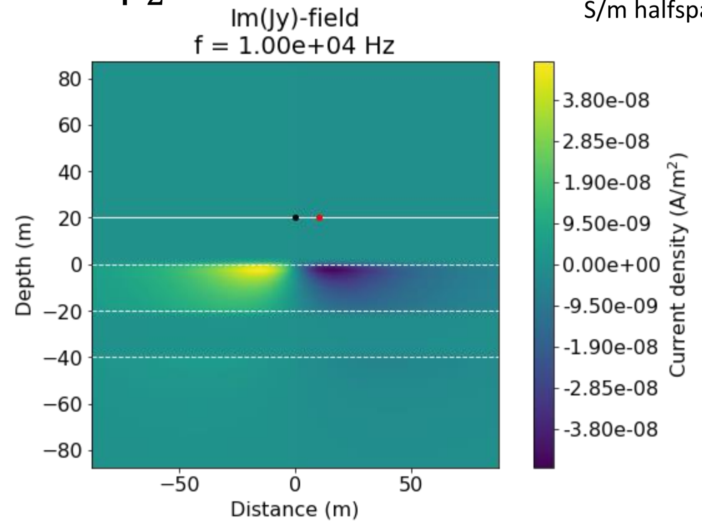
Current density (J_y imag)

Images created using FDEM_VMD_LayeredEarth.ipynb, 0.01 S/m halfspace, VMD height 20 m.

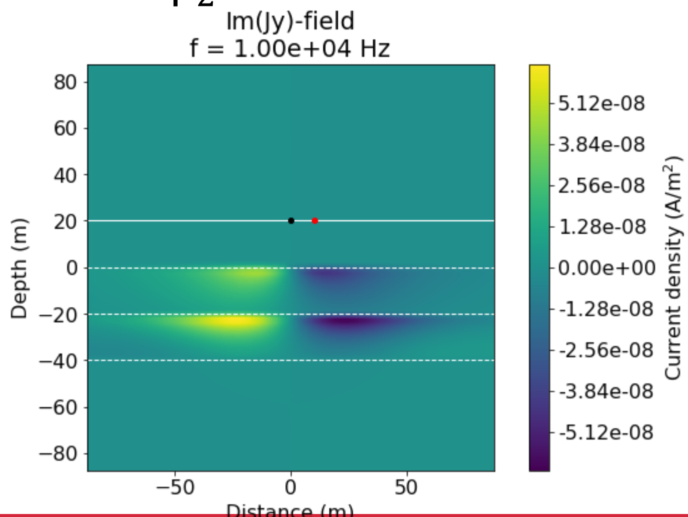
ρ_2 = 100 Ωm



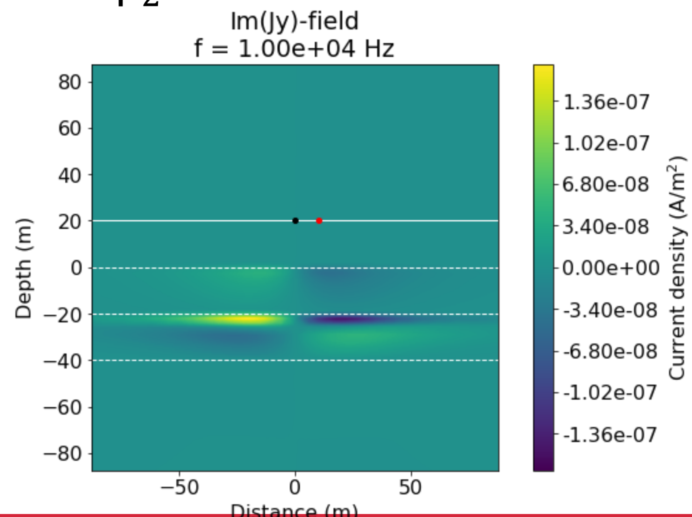
ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm

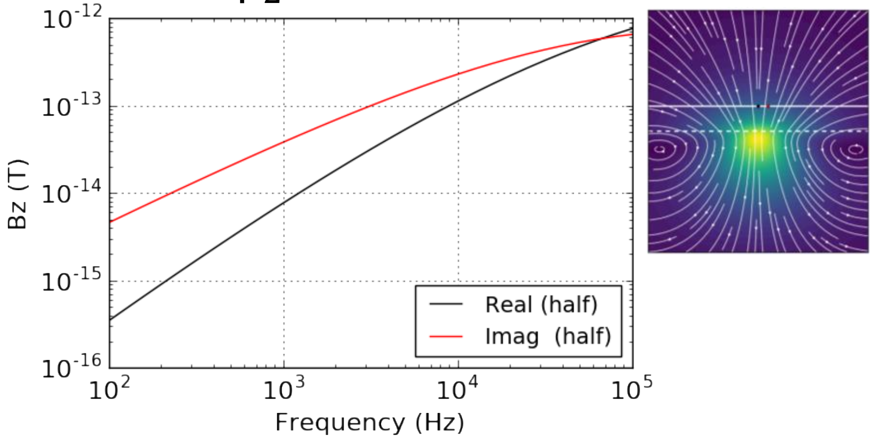


ρ_2 = 1 Ωm

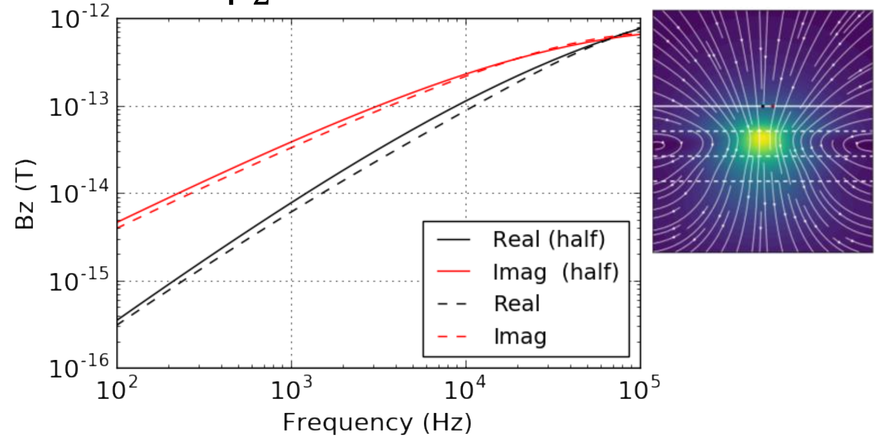


B_z sounding curves

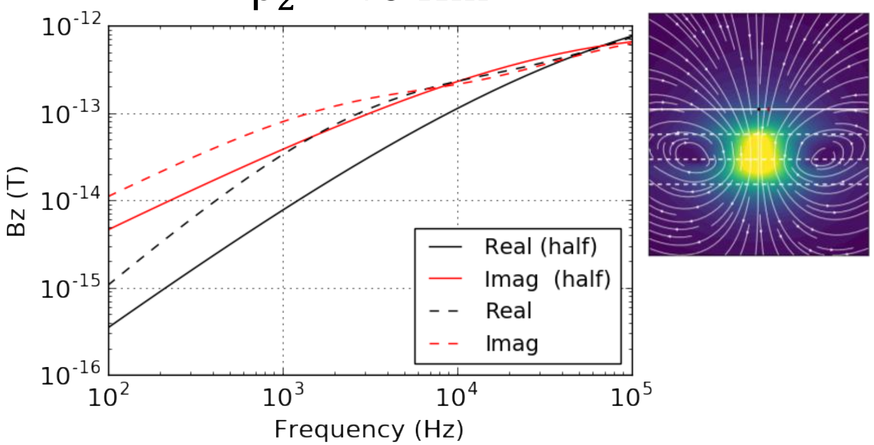
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm



ρ_2 = 1 Ωm

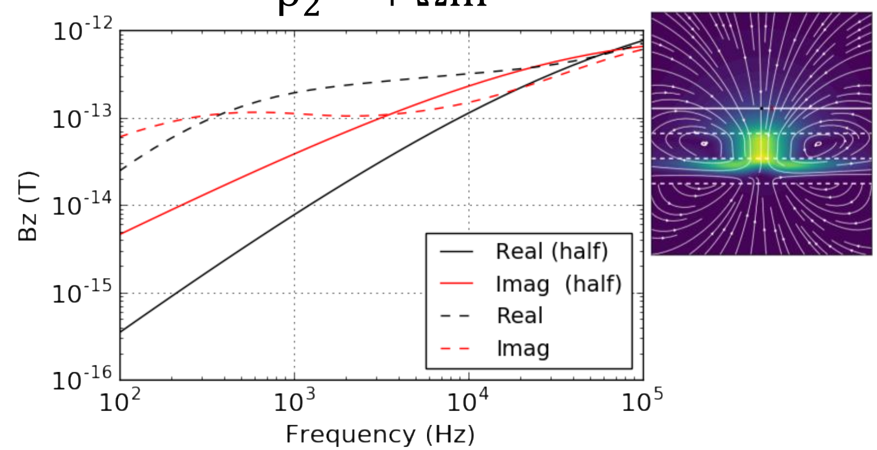
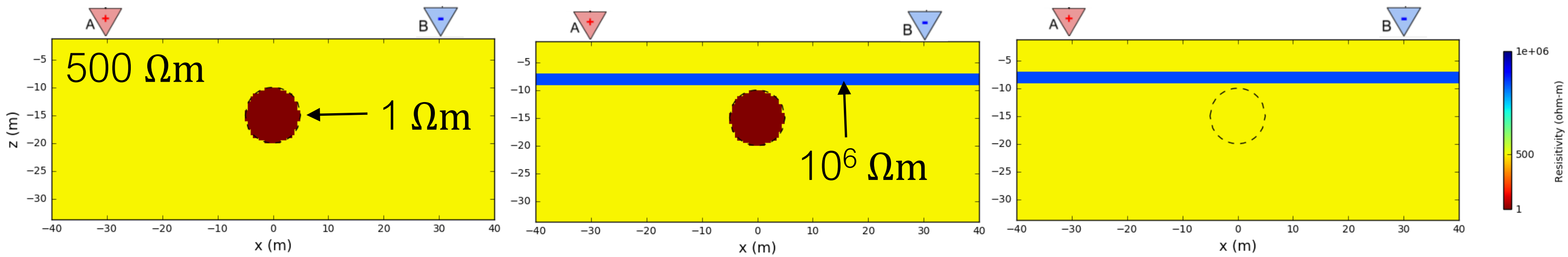


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

ρ_a = 430 Ωm　　ρ_a = 1652 Ωm　　ρ_a = 1654 Ωm

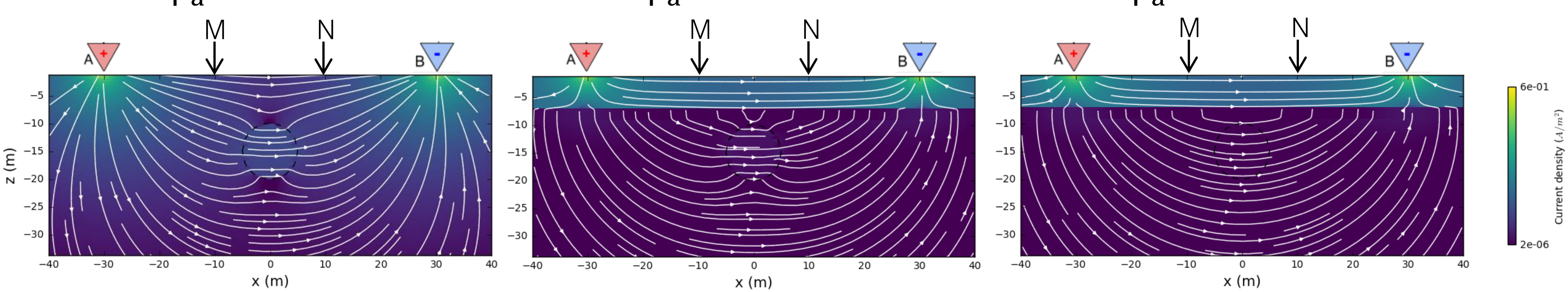
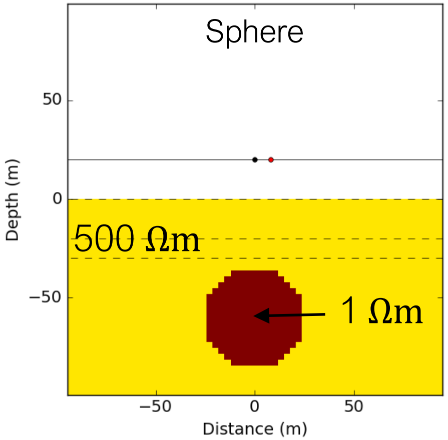


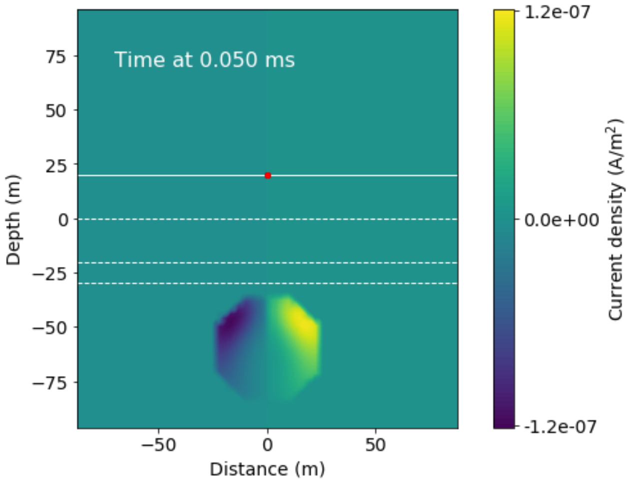
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

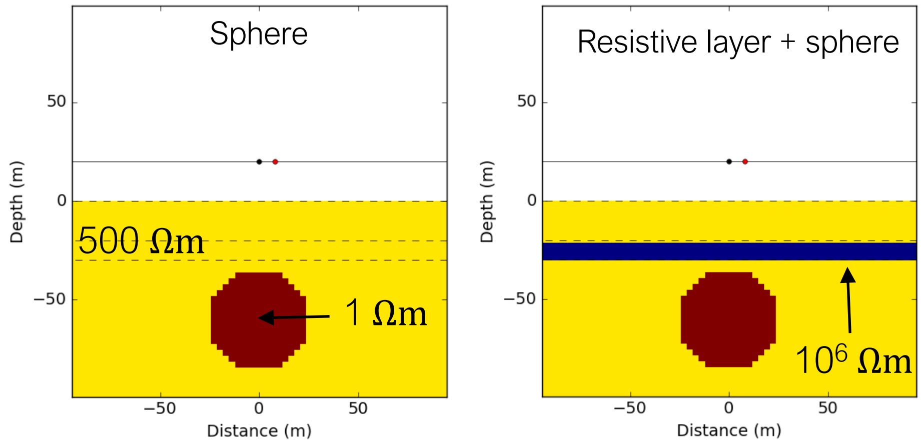


Currents (J_y)

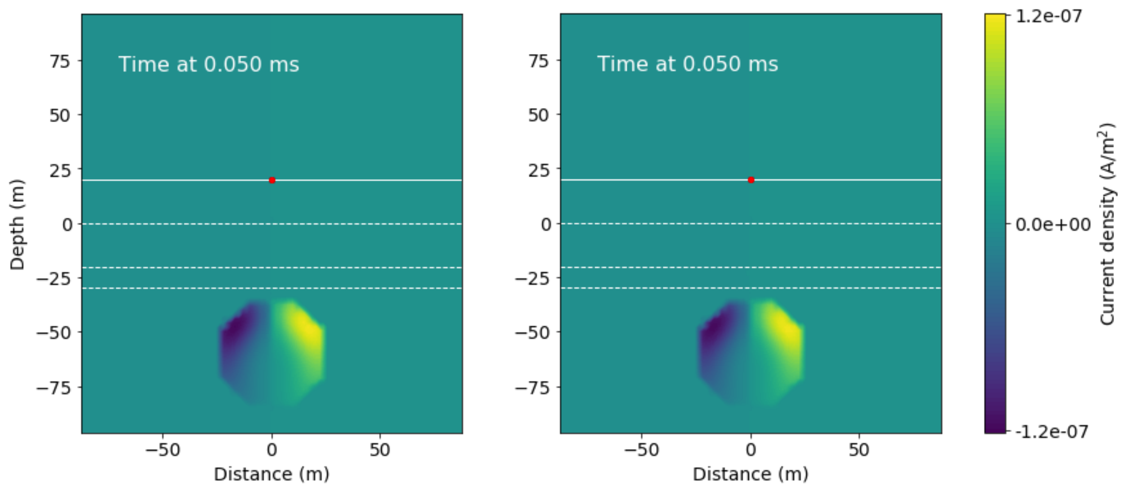


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

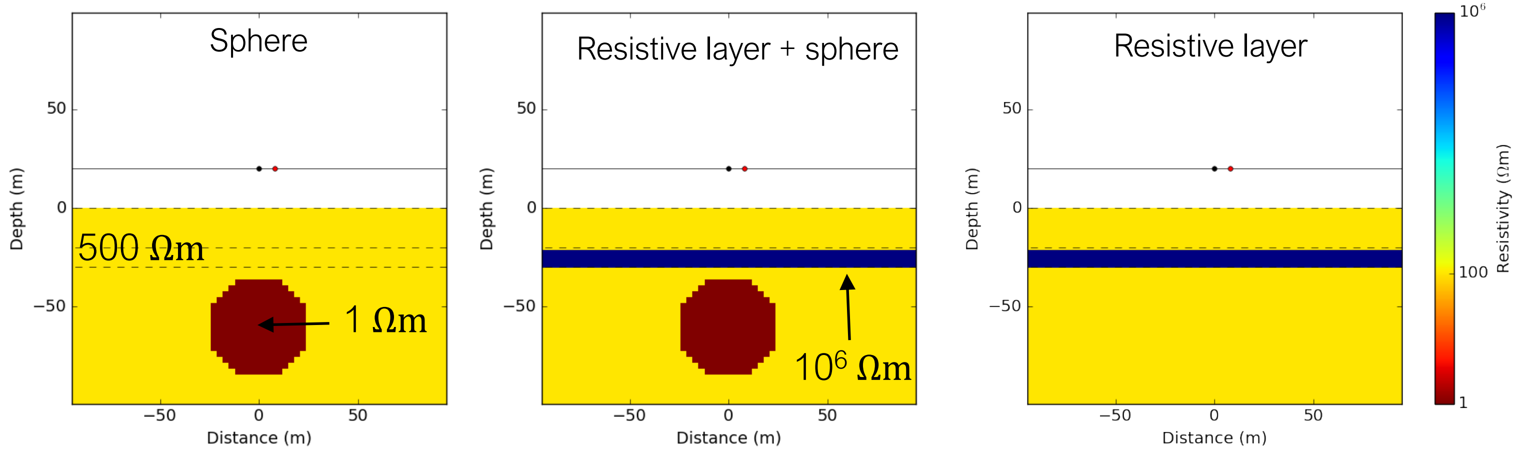


Currents (J_y)

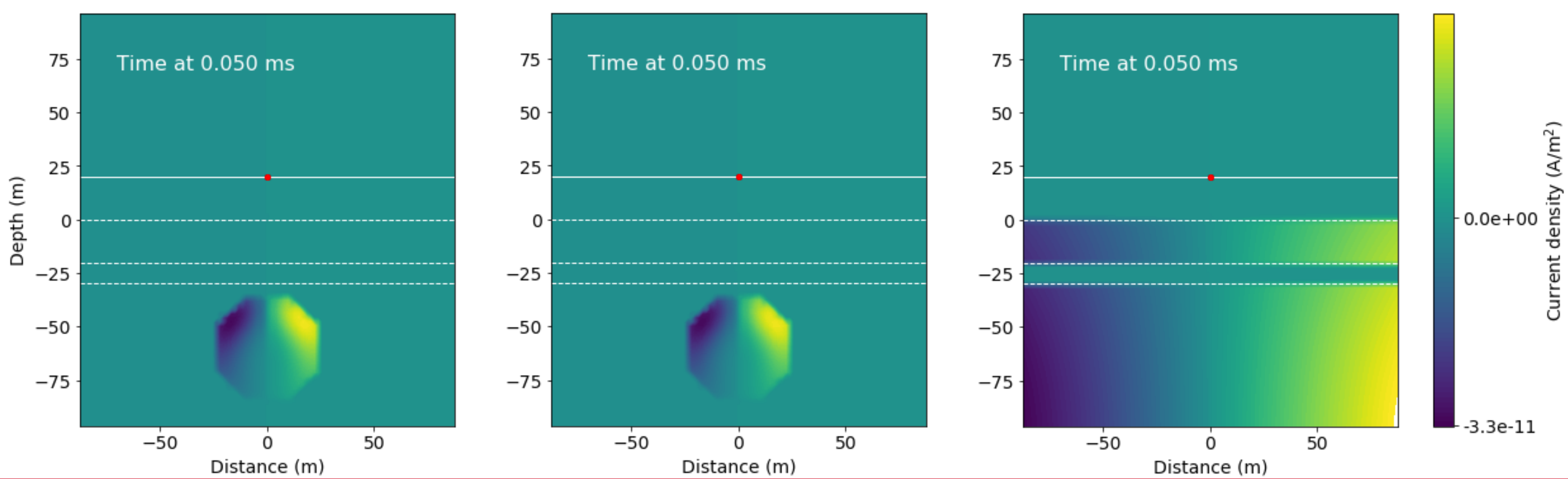


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

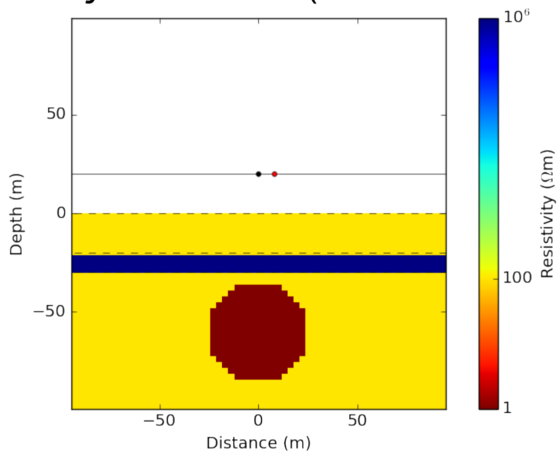


Currents (J_y)

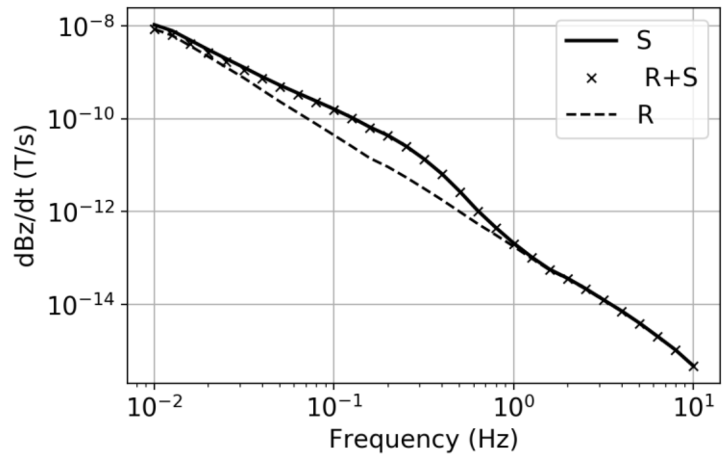


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)



db_z/dt sounding curves

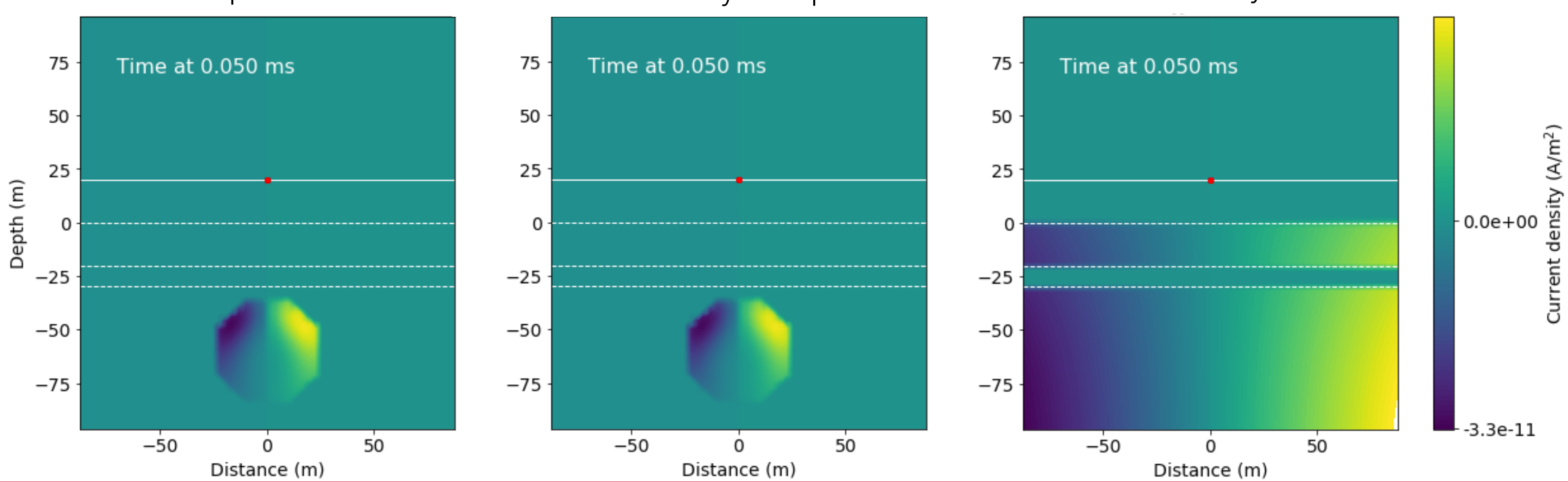


Currents (J_y)

Sphere

Resistive layer + sphere

Resistive layer



Agenda

- DC resistivity
- RL circuit
- Plane waves
- Inductive source EM
- Grounded source EM

Grounded source EM

- What is grounded source?
- How does current change with time in the Earth?
- Secondary charges built-up
- Helps find resistors

From DC and inductive source to grounded source

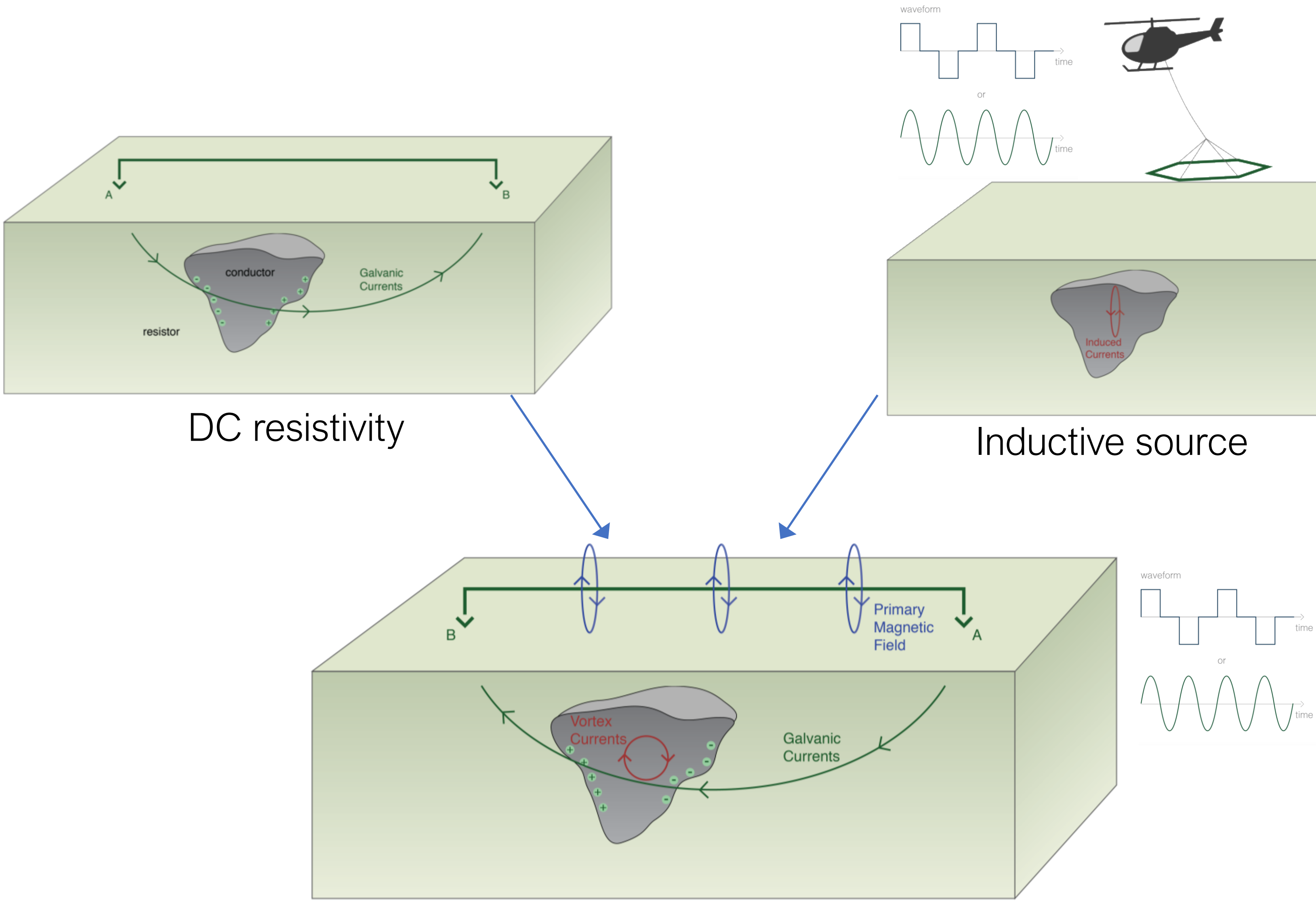
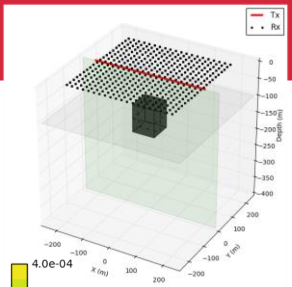


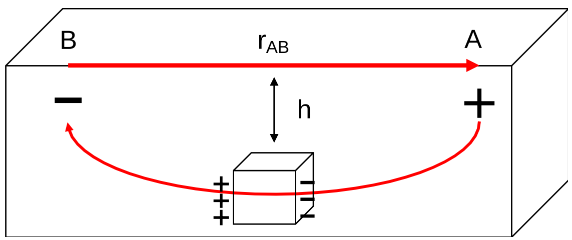
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF



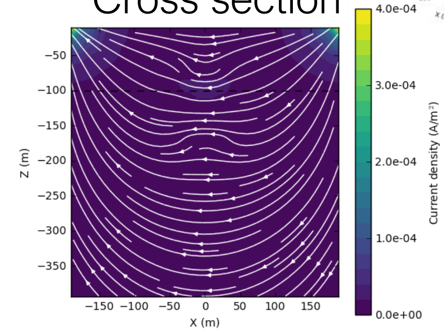
Conductor: currents

Cross section

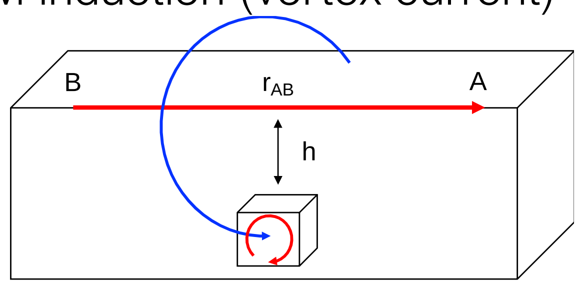
Steady State (galvanic current)



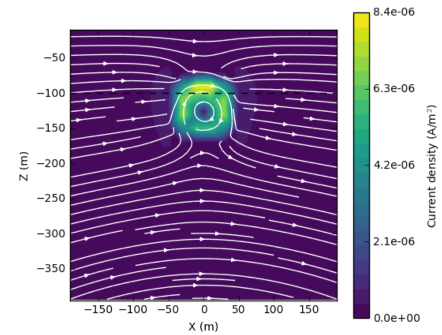
Galvanic current
t = 0$^-$



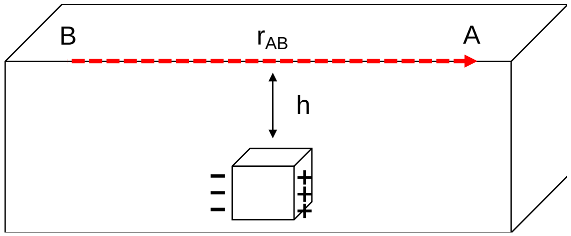
EM induction (vortex current)



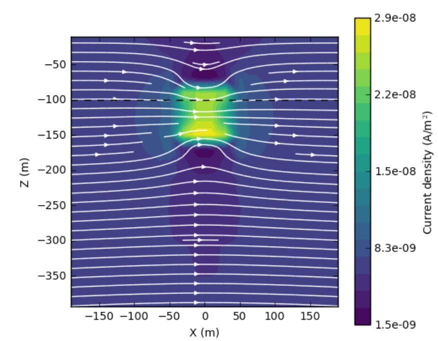
Vortex current
t = 1 ms



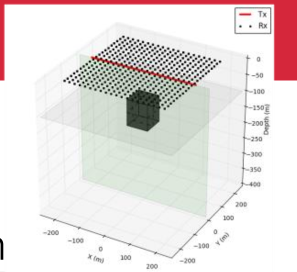
EM induction (galvanic current)



Galvanic current
t = 10 ms

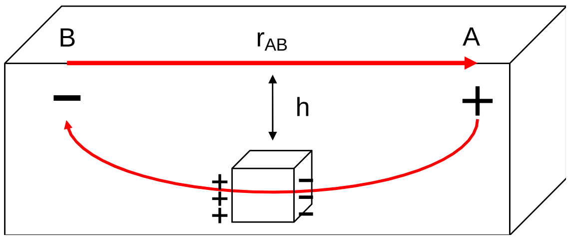


Resistor: currents

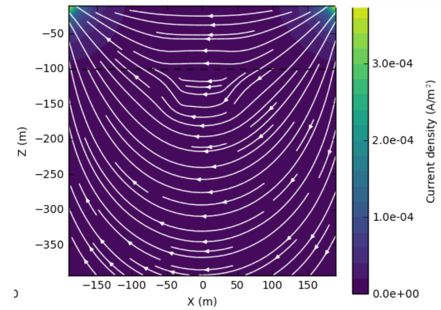


Cross section

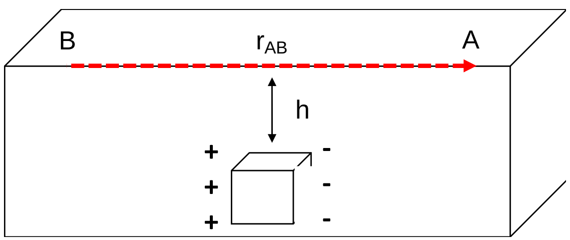
DC (galvanic current)



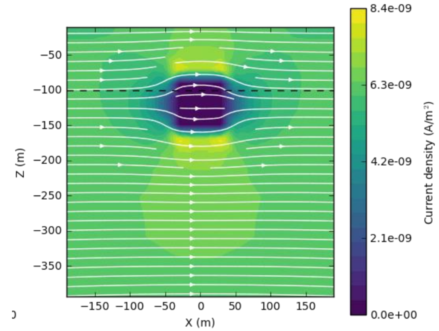
Galvanic current
$t = 0^-$



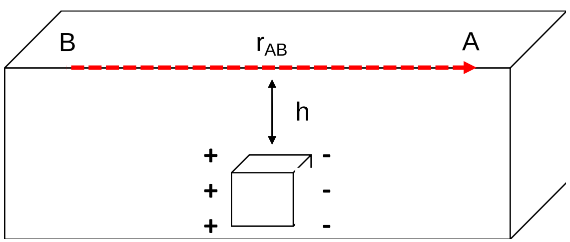
EM induction (galvanic current)



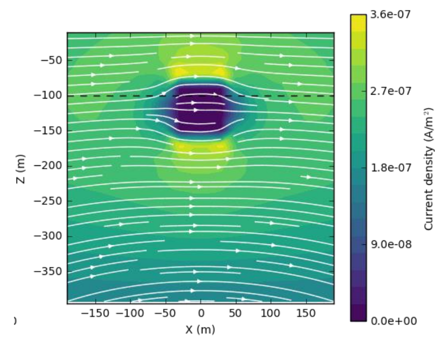
Galvanic current
t = 1 ms



EM induction (galvanic current)

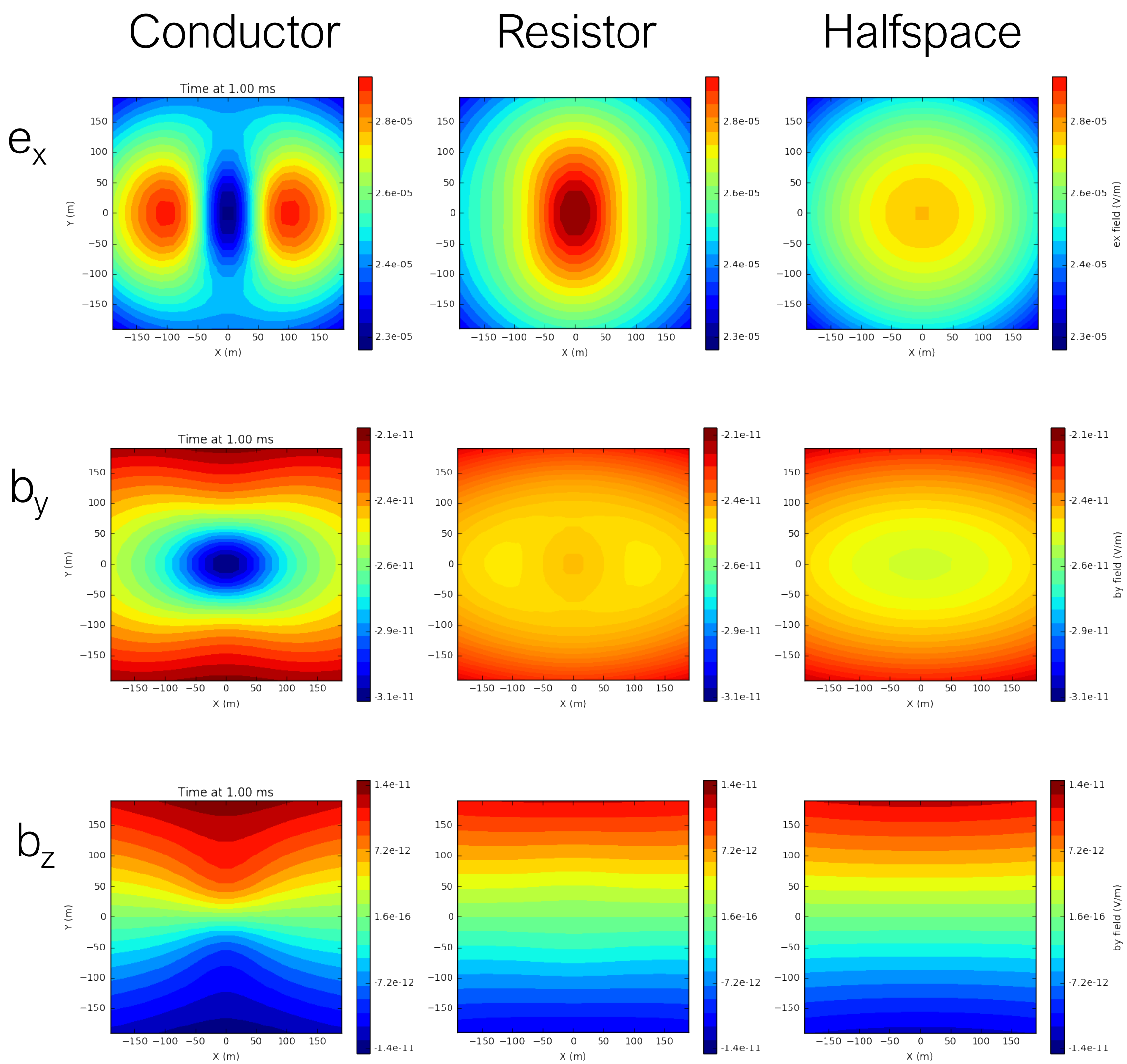


Galvanic current
t = 10 ms



Data summary

t = 1ms



Summary

- Ex, By are more sensitive to conductor than resistor.
- Ex is more sensitive to resistor (than By and Bz).

- To look for a resistive target, E-field measurements are more useful.

- Finding resistors is more challenging than conductors, but with grounded sources, we now can find resistors!!